Vector Boson Scattering at the LHC

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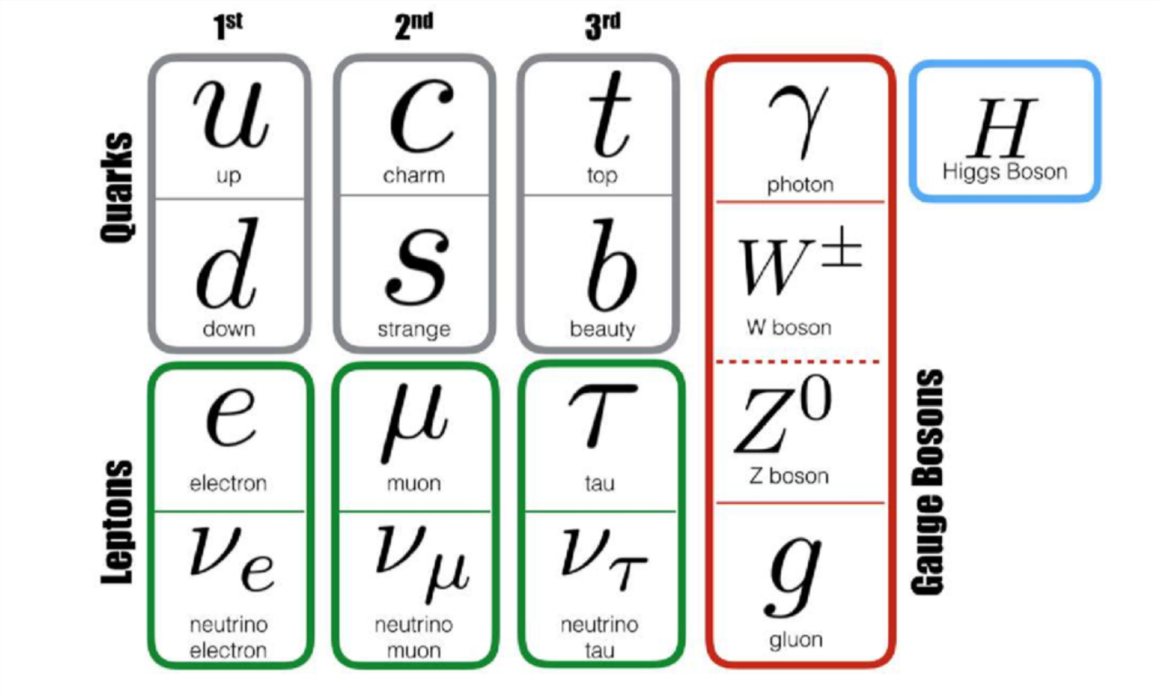
Overview

- The Vector Boson Scattering
    - Theoretical motivation
    - Experimental and theoretical challenges
- ATLAS and CMS results and interpretation
- Plans for the future
    - Interaction with theorists
    - Experimental improvement of the analyses
    - Plans with respect to the LHC timeline

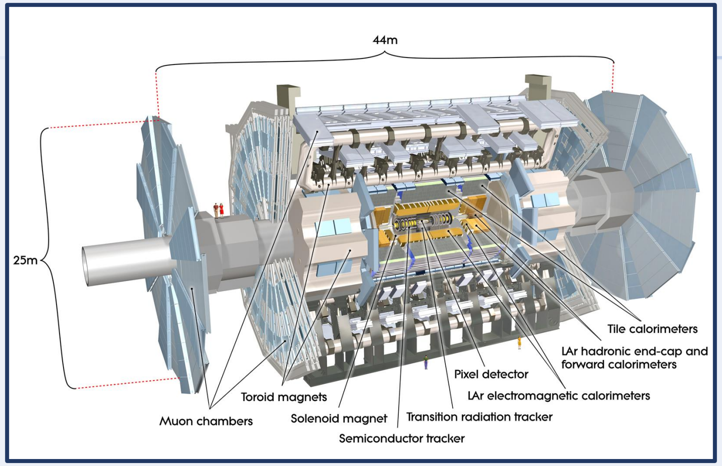
The Standard Model and its limits

- A long history of successes
- A perfect completeness with the Higgs boson discovery
- Accepted to be valid up to certain, high, energy scale Λ



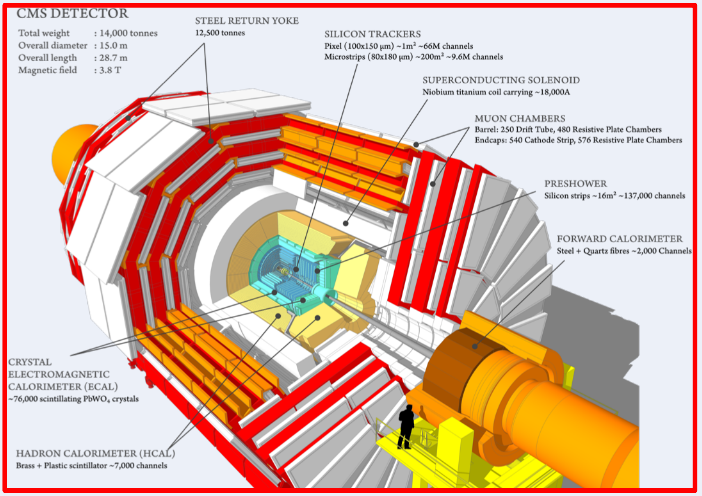
- Nevertheless, there is no doubt that there is something to discover beyond the SM:
  - ✓Neutrino mass and matter/antimatter asymmetry are only a few examples
- What kind of new physics is that introduces those deviances from the SM?
- How can this new physics be observed and measured?

The Large Hadron Collider



A Toroidal LHC ApparatuS

Compact Muon Solenoid

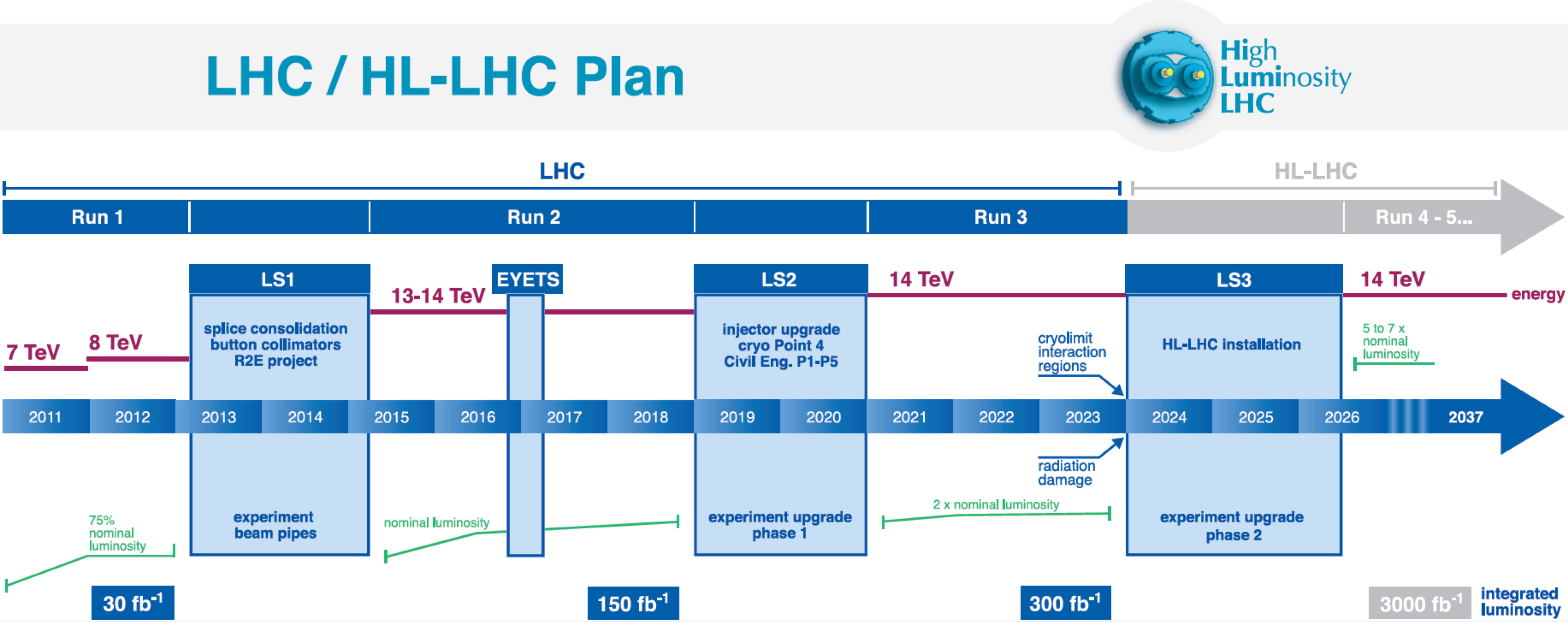


LHC: a proton-proton collider (CERN)

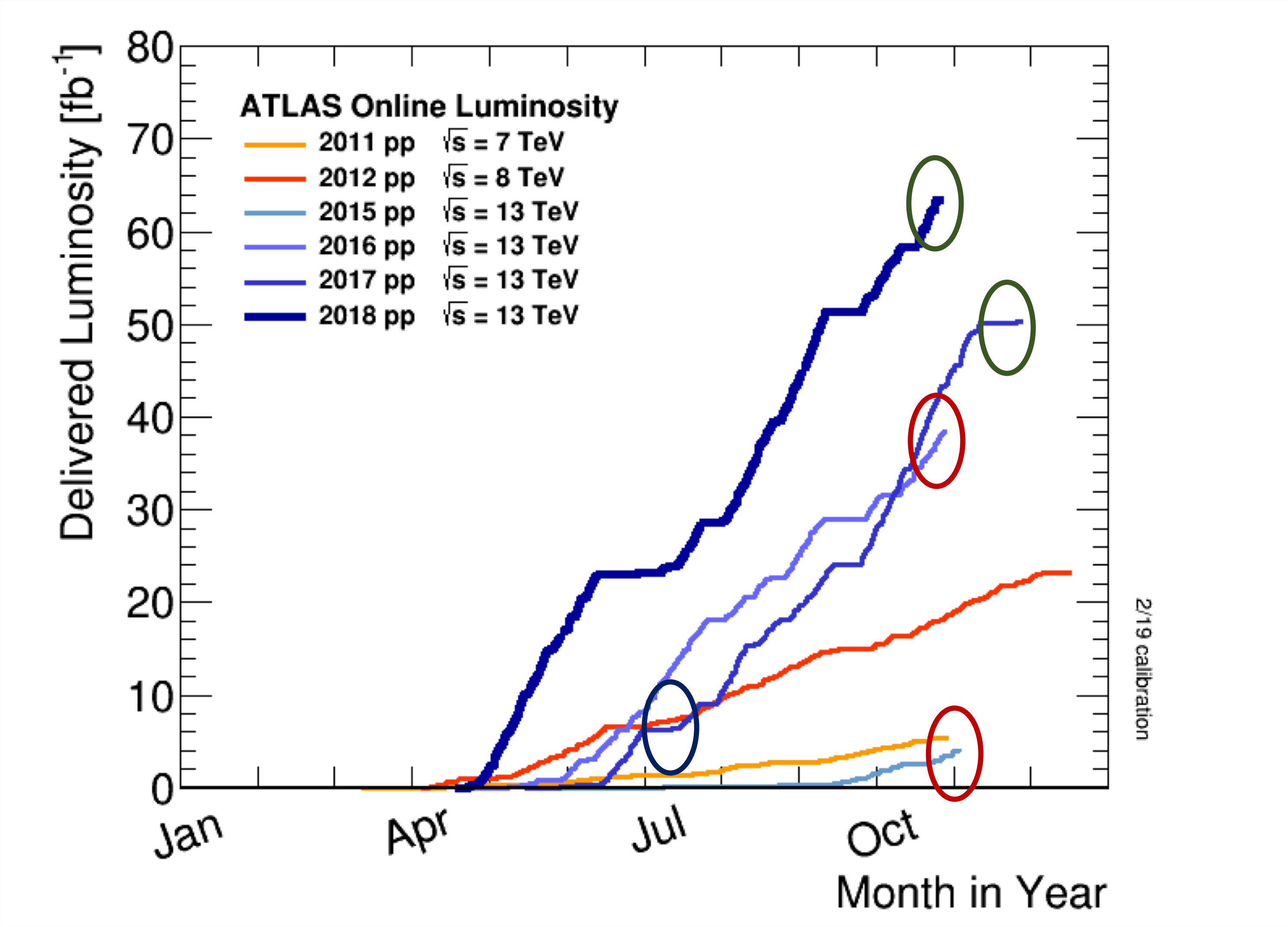
✓ 13 TeV center-of-mass-energy since 2015

✓ 40 M collisions every second

The Large Hadron Collider



A lot more possibilities since the Higgs discovery



July 2012 :

Higgs boson discovery

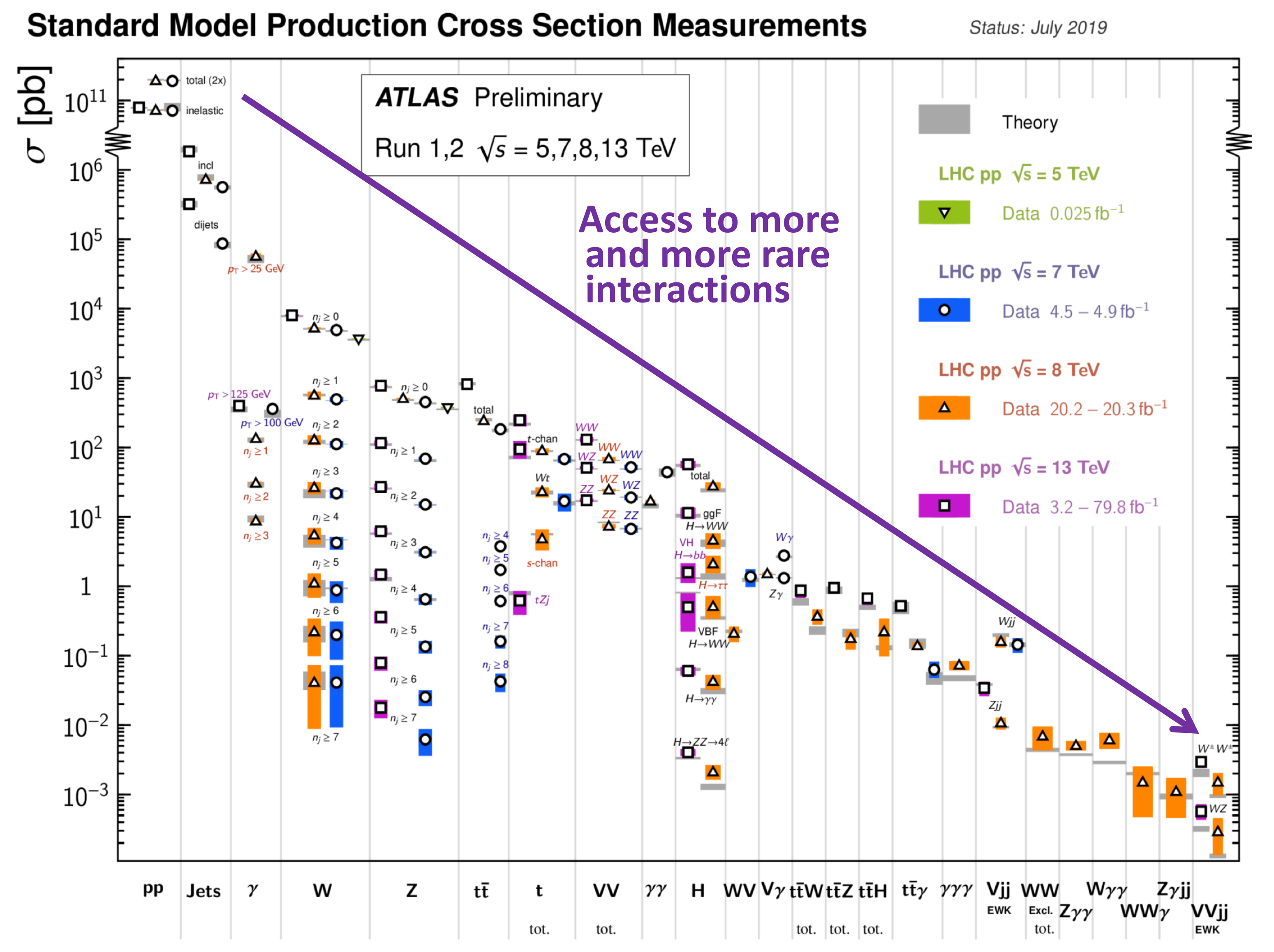
End of 2016 :

3 times higher integrated luminosity

End of 2018 :

14 times higher integrated luminosity

A lot more possibilities since the Higgs discovery

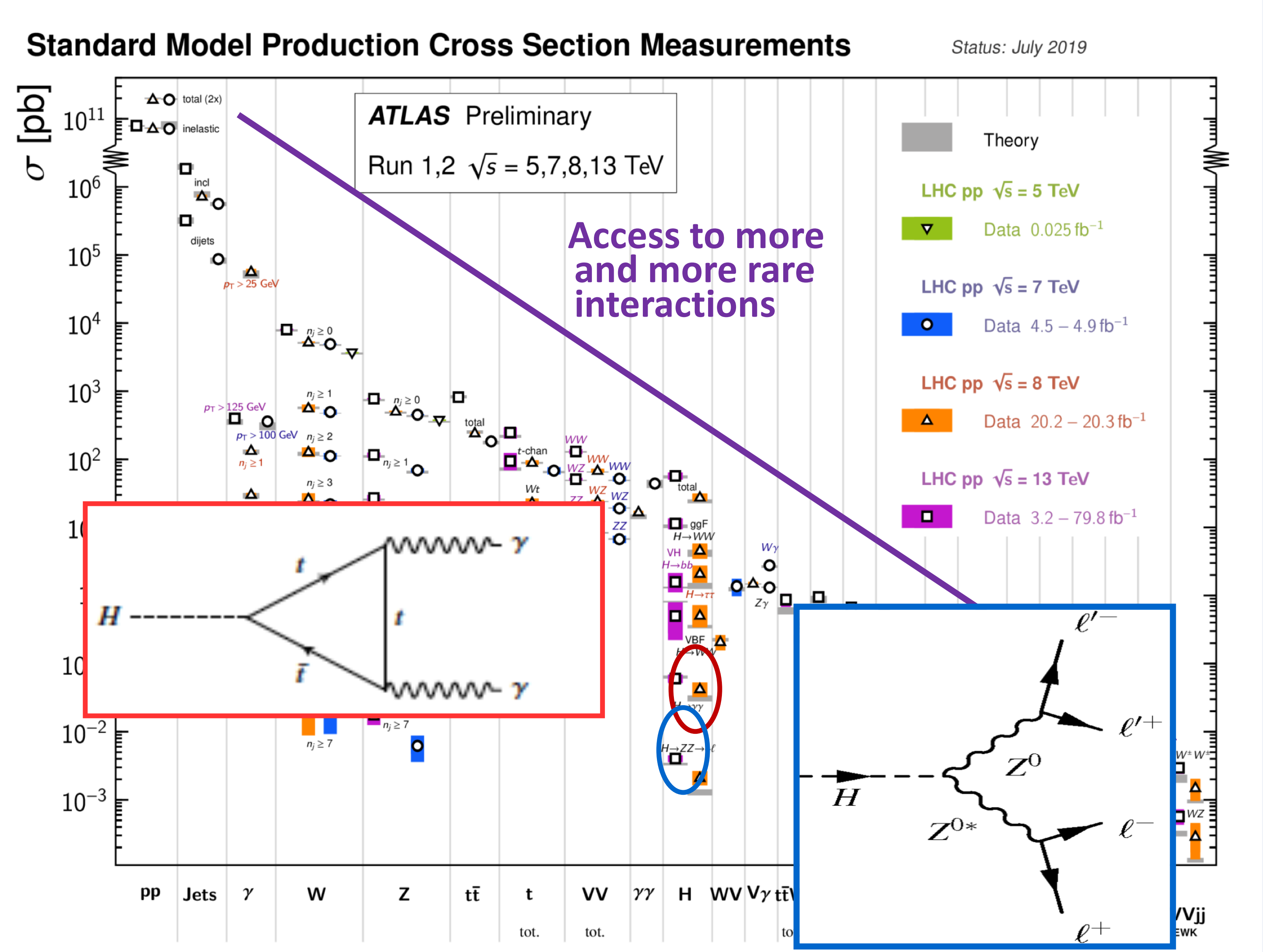


Access to more and more rare interactions

With this high luminosity:

- Explore the Higgs sector
- Improve the precision on already observed processes
- Look for never observed, rare processes:
  - ✓ Predicted by the SM
  - ✓ Only existing as part of new physics

A lot more possibilities since the Higgs discovery



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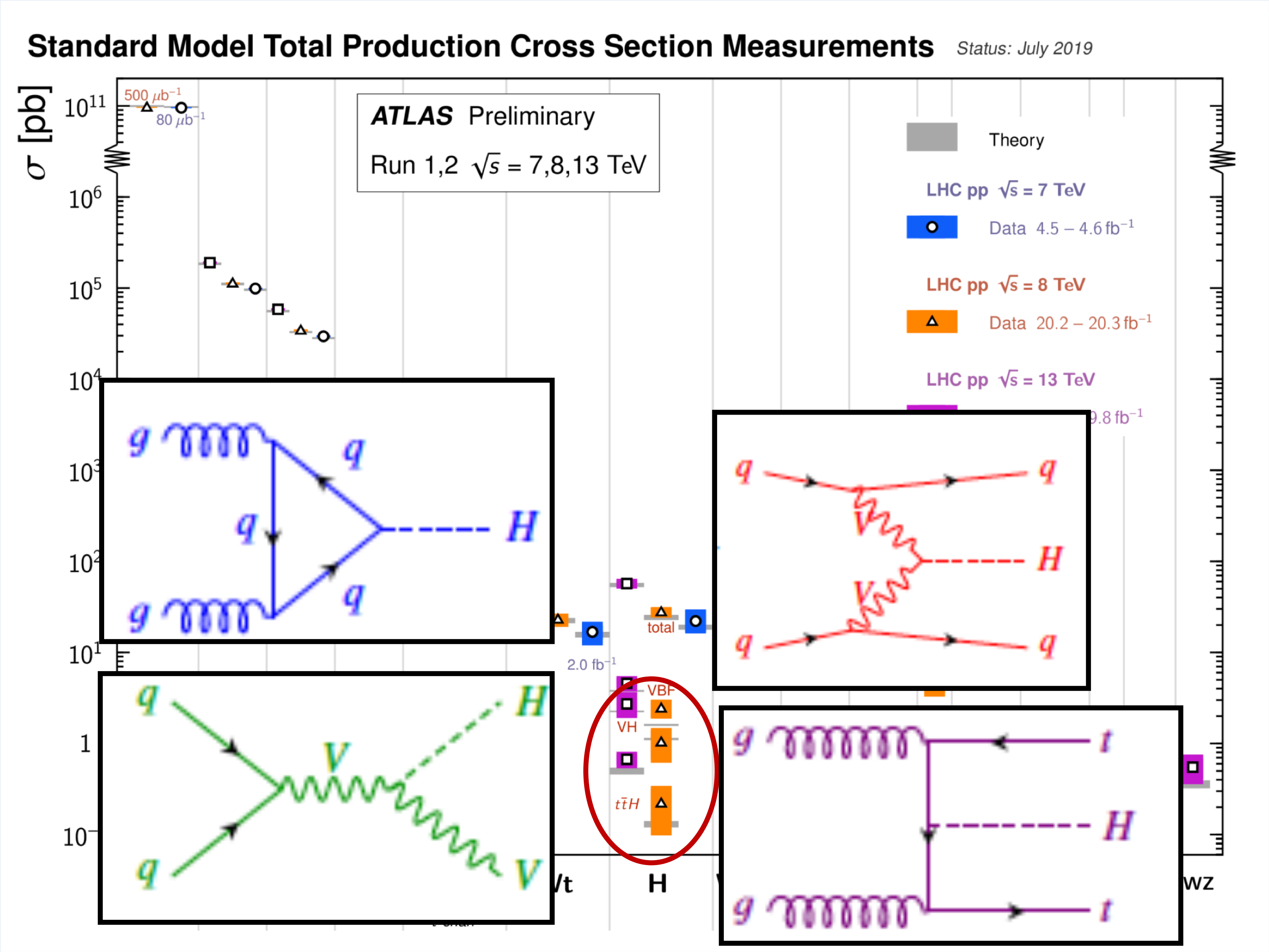
With this high luminosity:

- **Explore the Higgs sector**

✓ only 200 évènements Higgs→γγ in 2012

✓ less than 10 to 4 leptons !

A lot more possibilities since the Higgs discovery



With this high luminosity:

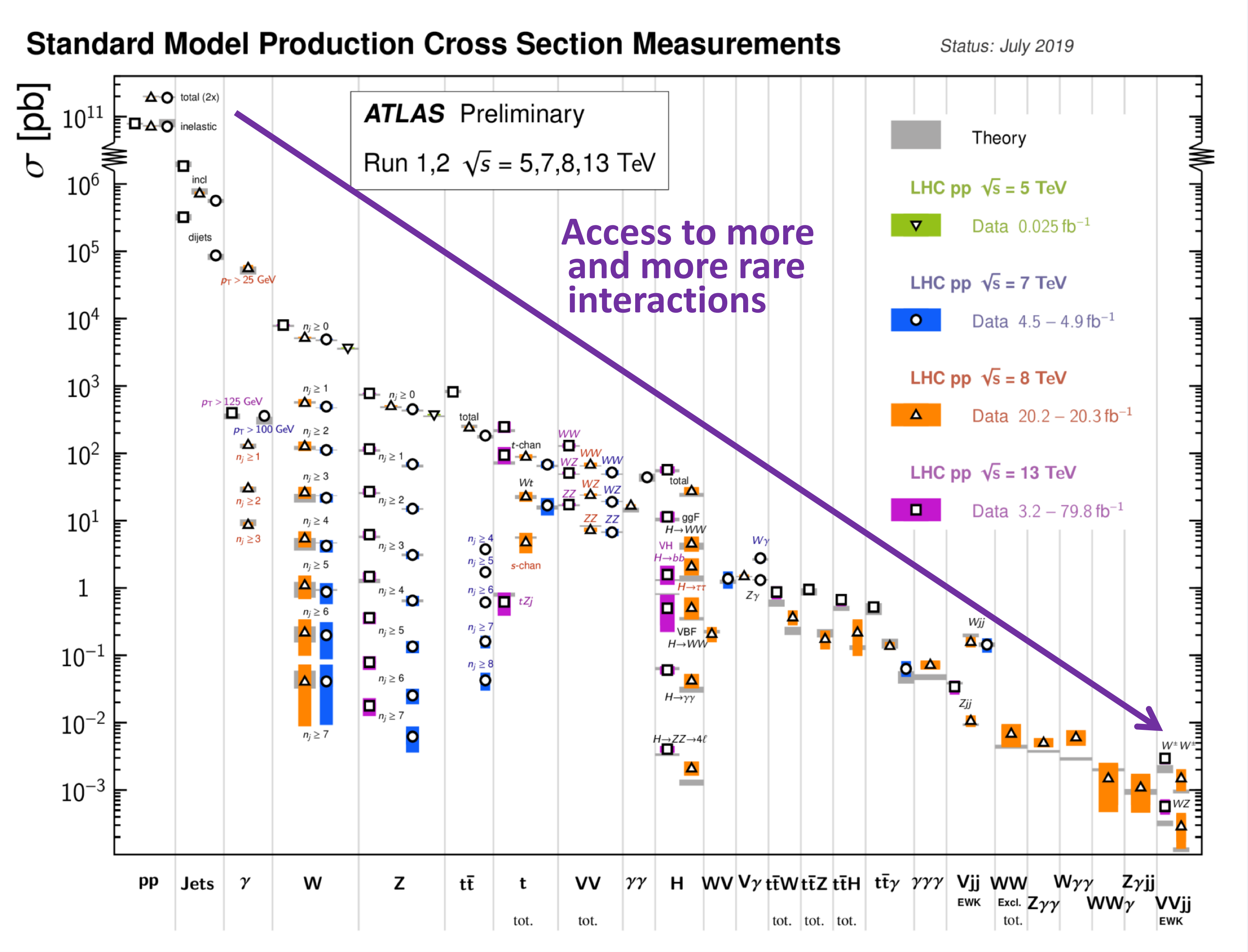
- **Explore the Higgs sector**

✓ only 200 évènements Higgs→γγ in 2012

✓ less than 10 to 4 leptons !

- Now we are able to separately study different production modes and are completing the Higgs couplings landscape

A lot more possibilities since the Higgs discovery



Access to more and more rare interactions

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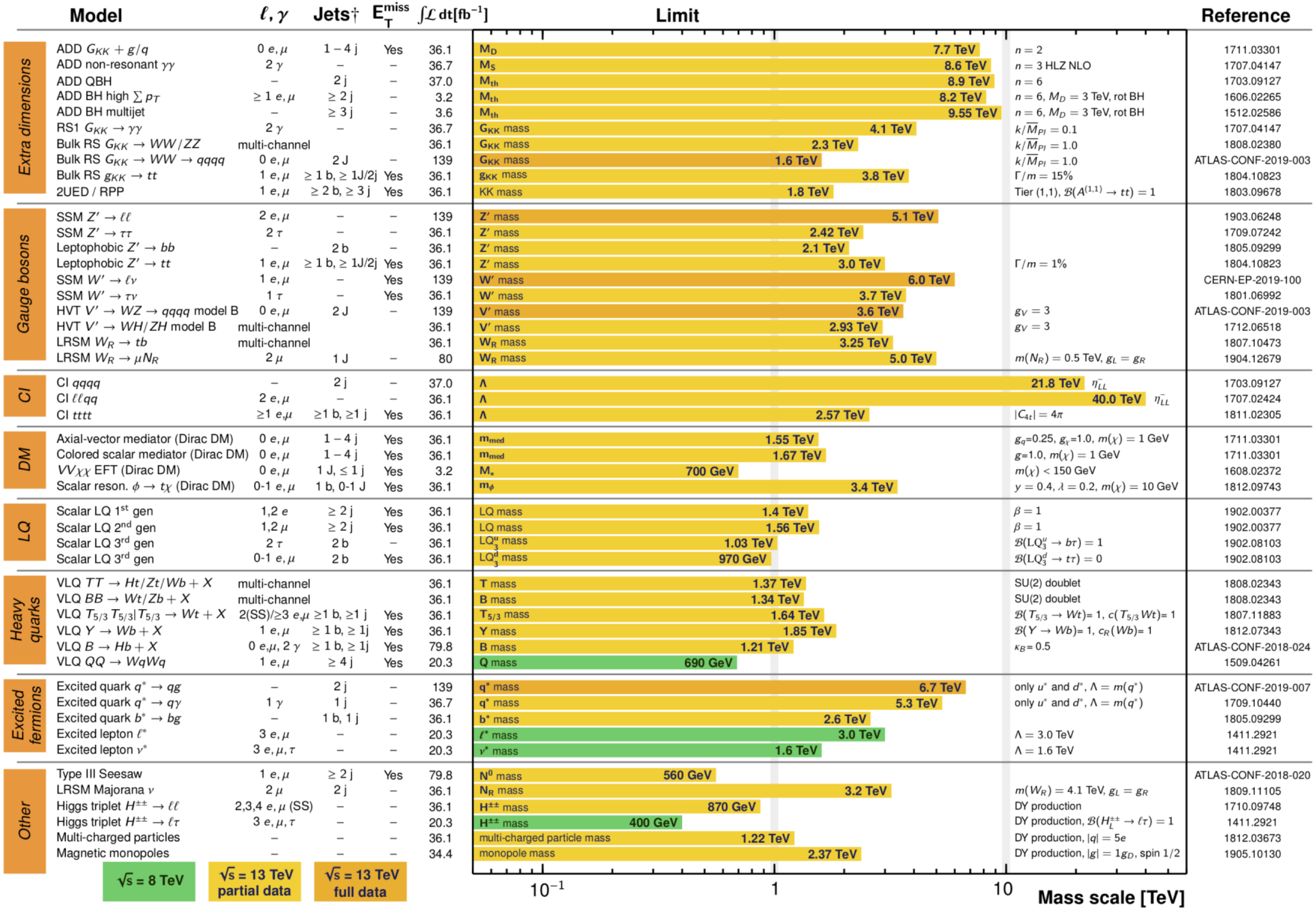
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

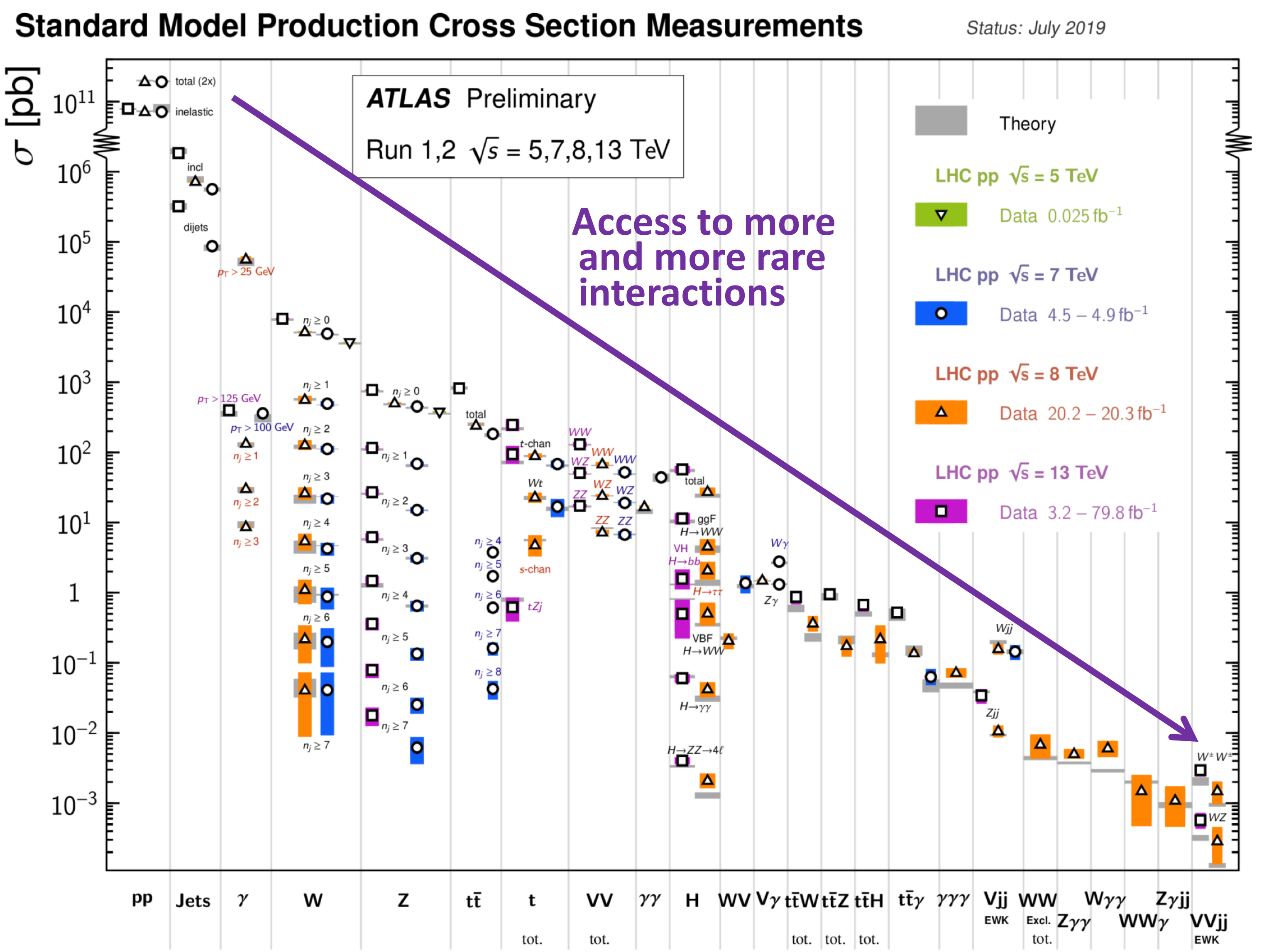


	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WW \to qqqq$	0 e, μ	2 J	–	139	G_{KK} mass 1.6 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		CERN-EP-2019-100
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WZ \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.6 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^-		1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.0 TeV η_{LL}^-		1707.02424
	CI $tttt$	≥1 e, μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e, μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q \rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

A lot more possibilities since the Higgs discovery



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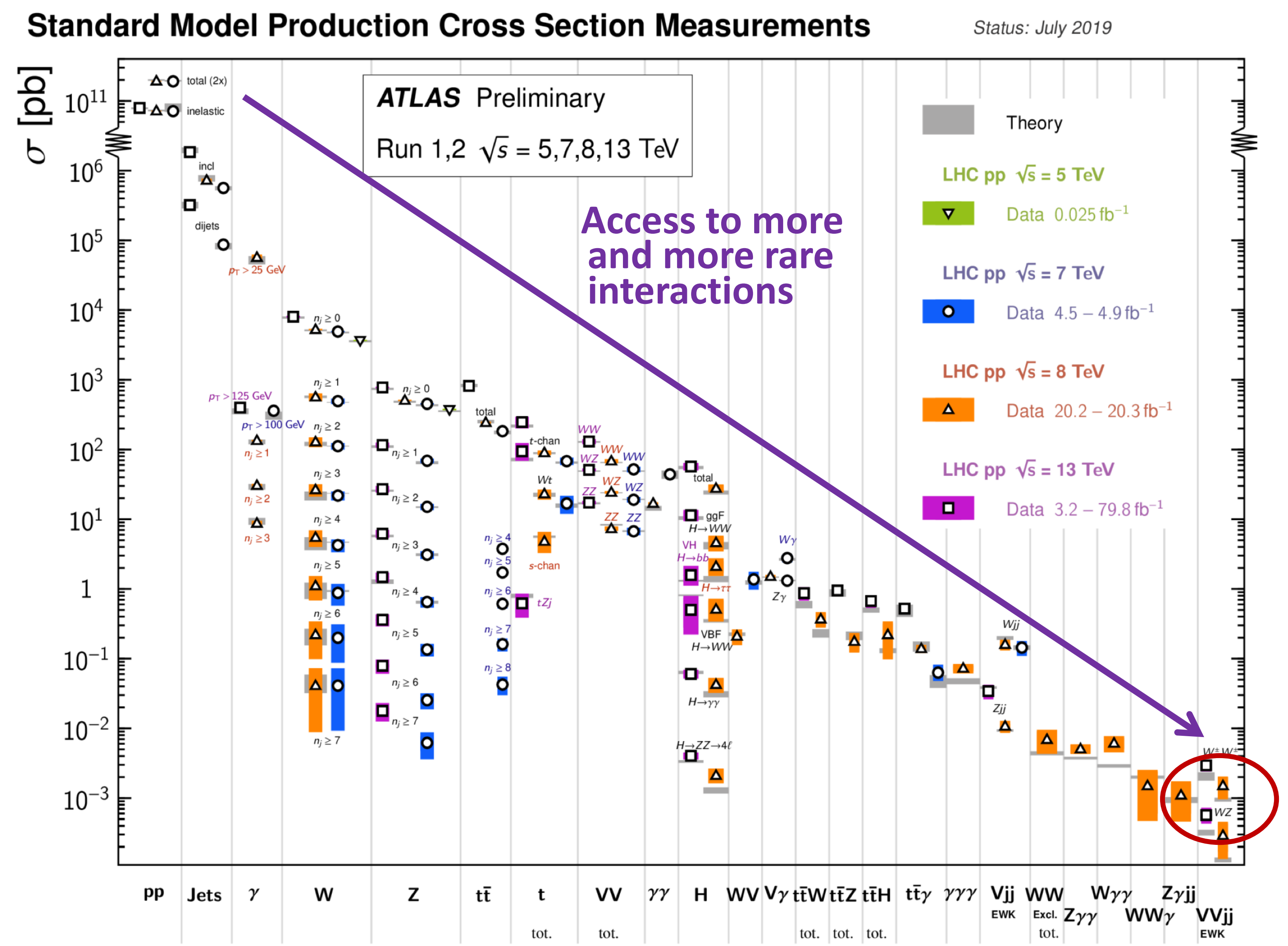

Access to more and more rare interactions

Electroweak diboson production

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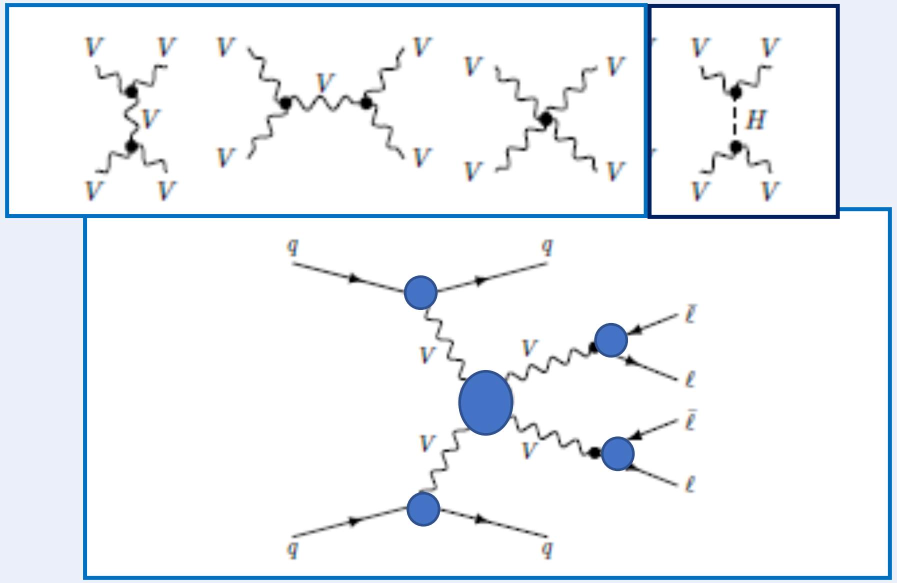
Electroweak diboson production

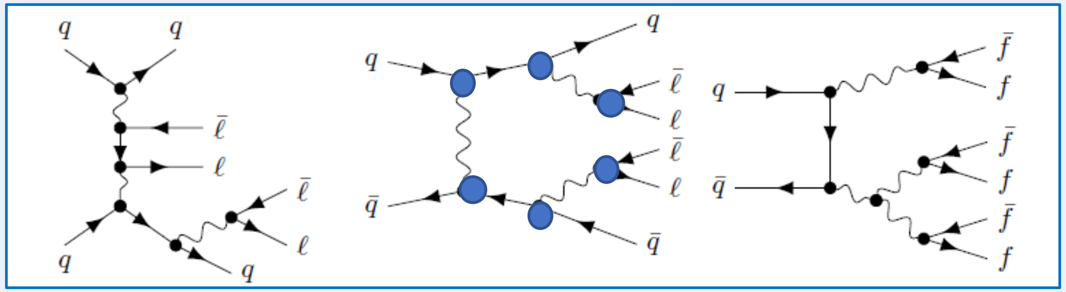
α_{EW} order: 6
α_s order: 0

Diboson production via **vector boson scattering**



- Very well described process with the Standard Model
- Deviation from prediction could be a sign of new physics

EW diboson production



- can’t be dissociated from VBS process
- observation and cross section measurements concern both groups of diagrams

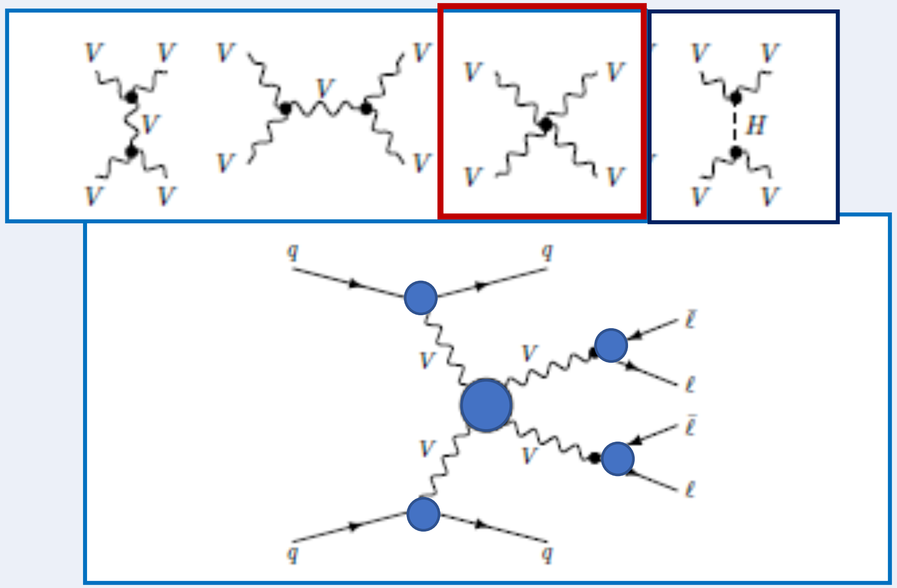
α_{EW} order: 6
α_s order: 0

Vector Boson Scattering

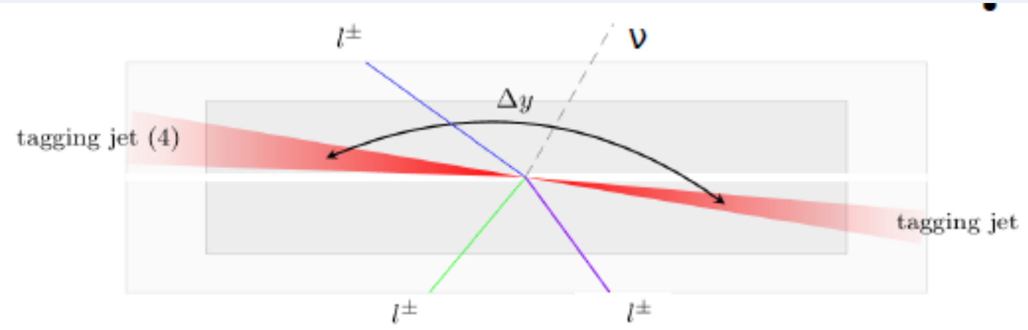
α_{EW} order: 6
α_s order: 0

Diboson production via vector boson scattering

- Very well described process with the Standard Model
- Deviation from prediction could be a sign of new physics

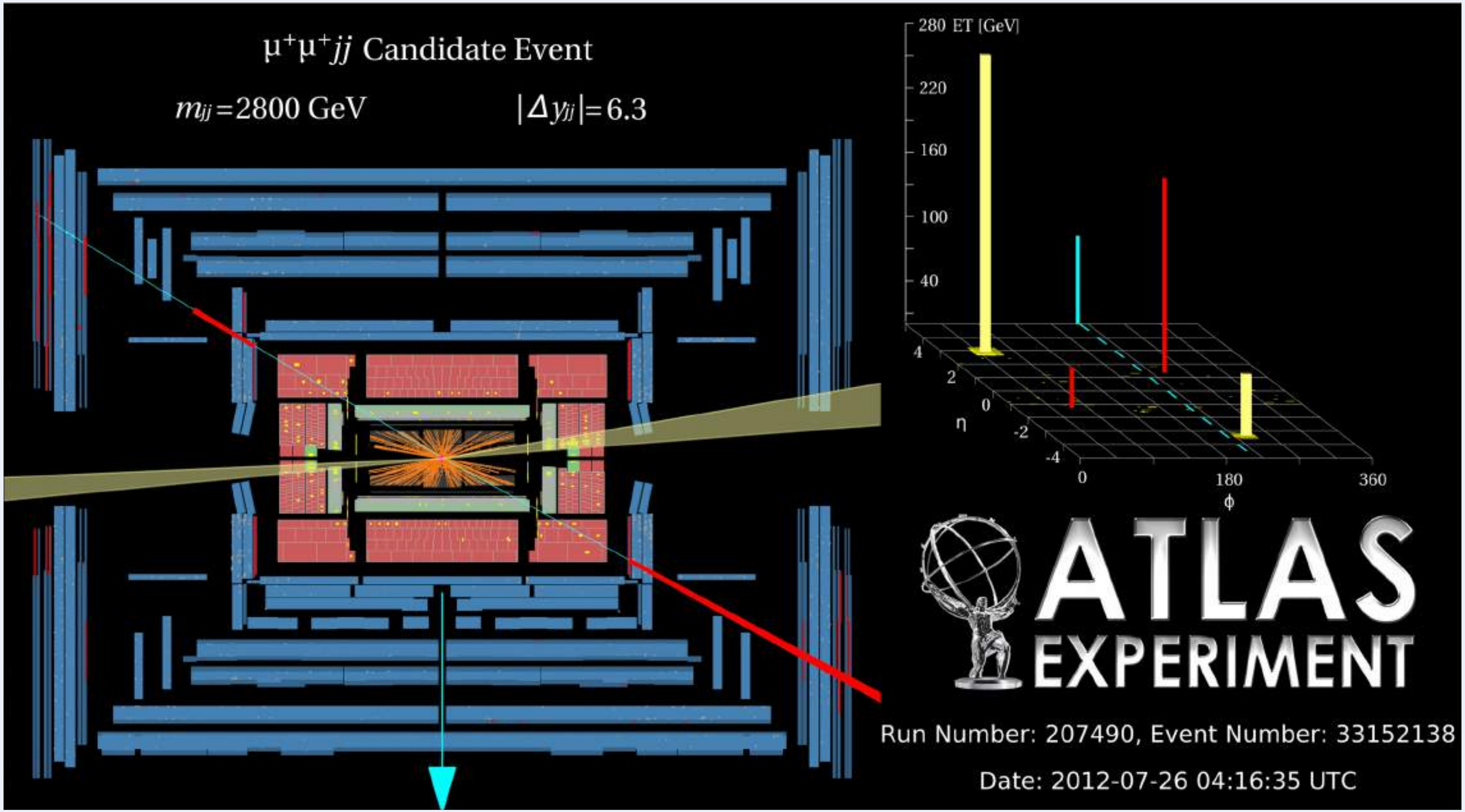


Very characteristic kinematical profil:



- Two high P_T forward jets (high Δη, high M_{jj})
- Diboson products in the central region

A typical VBS event (W^+W^+jj)

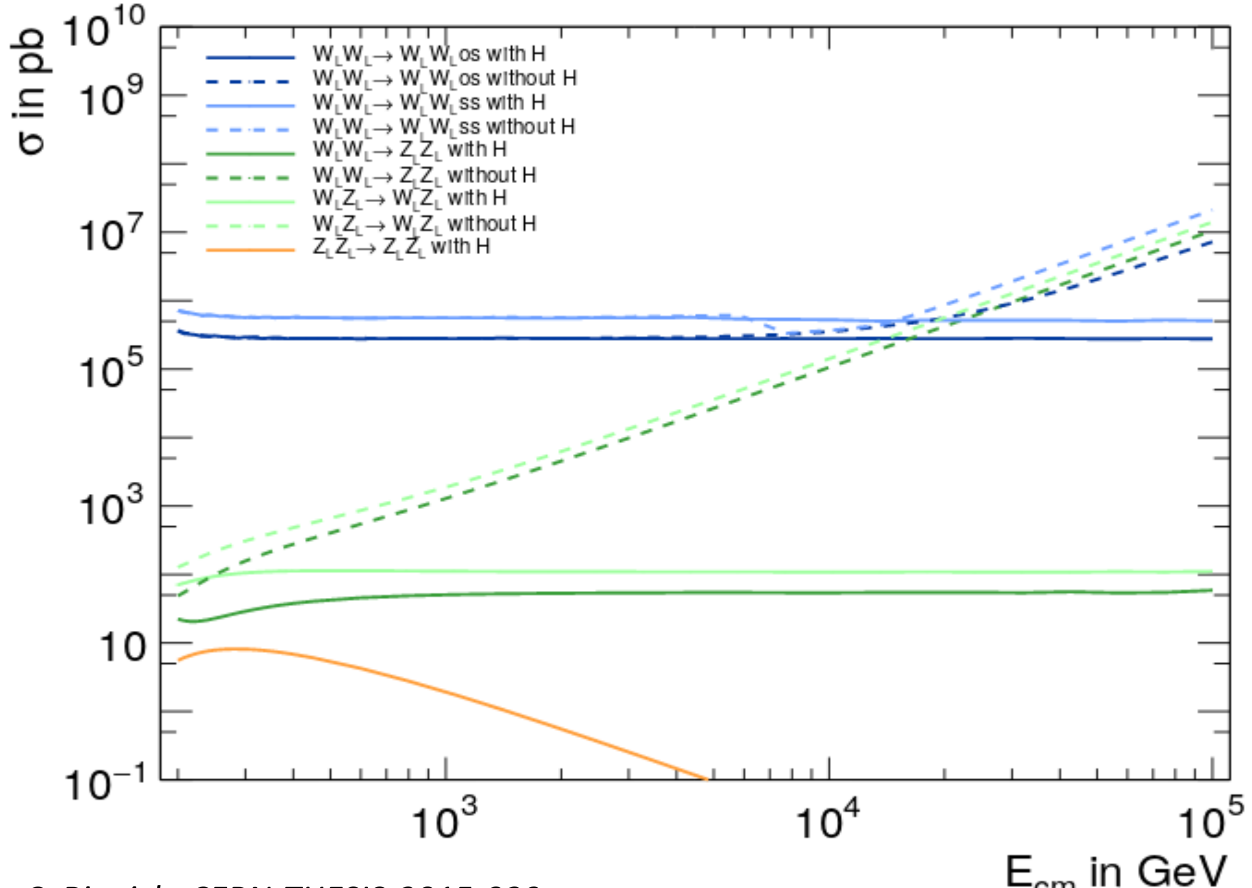


Vector Boson Scattering

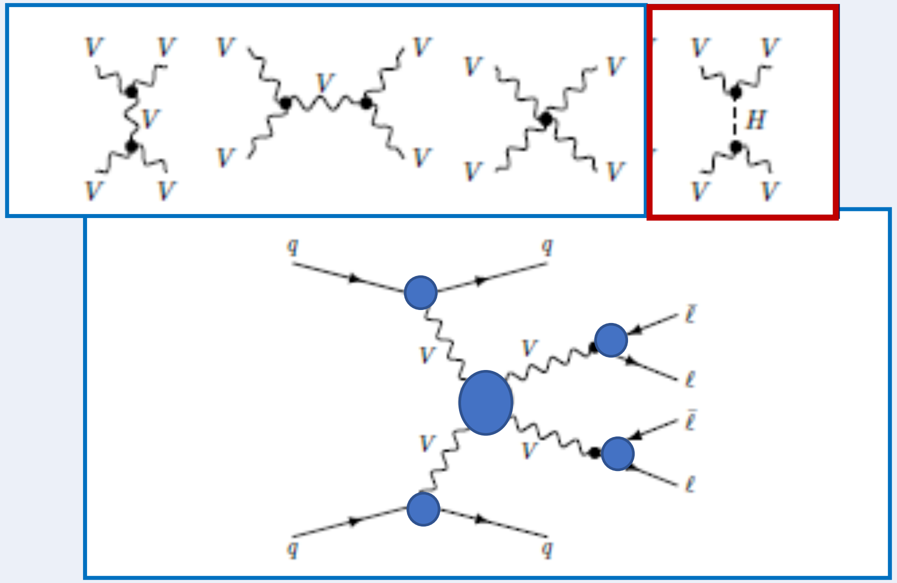
α_{EW} order: 6
α_s order: 0

Diboson production via vector boson scattering

EW sym. breaking sector: unitarity



C. Bittrich, CERN-THESIS-2015-039



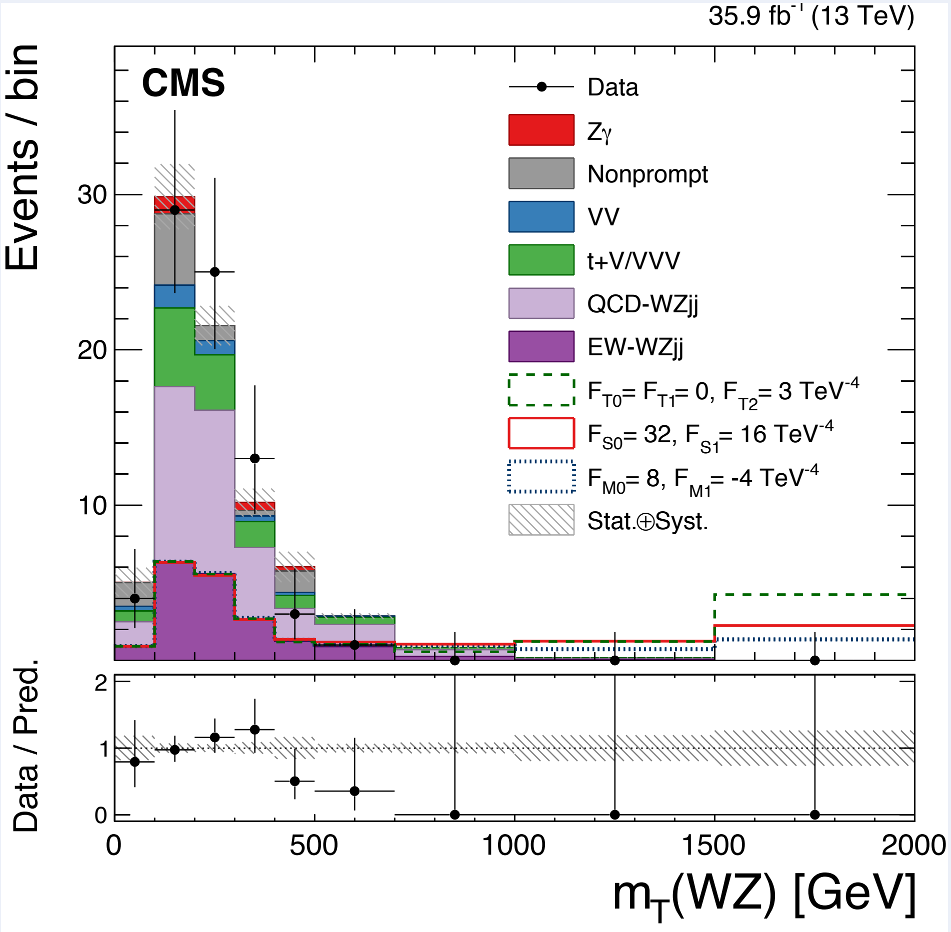
- Can be used to constraint non SM Higgs Models with enhanced couplings to vector boson
- Could be used as an indirect probe of Higgs properties, through longitudinally-polarized boson scattering (need higher integrated luminosity)

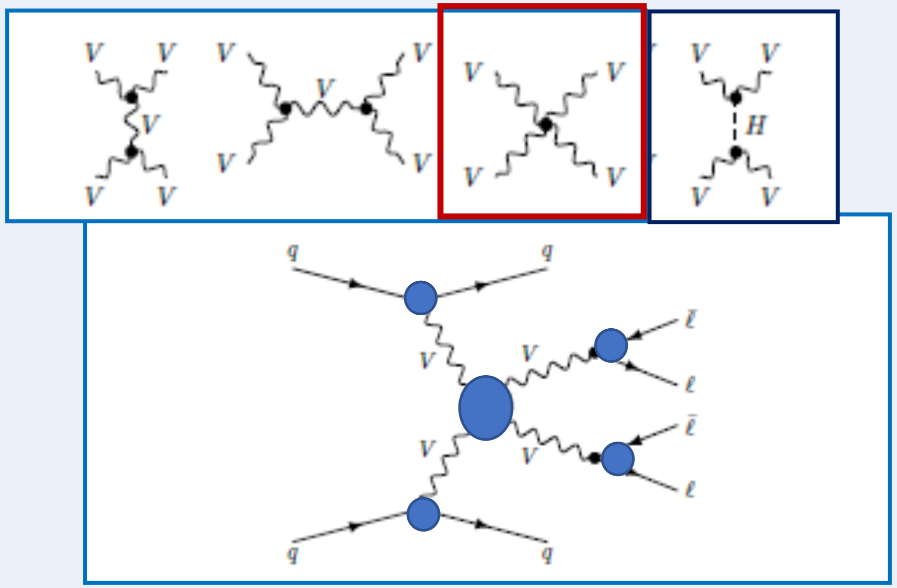
Vector Boson Scattering

α_{EW} order: 6
α_s order: 0

Diboson production via vector boson scattering

access to Quartic Gauge Couplings





- **Quartic Gauge Couplings** could be modified by new physics
  →anomalous QGC
- Effect on high energy tails of kinematical distribution such as M_{jj}
- ATLAS and CMS choice for interpretation: Effective Field Theory

VBS: Quartic Gauge boson Couplings (QGC)

- Anomalous QGC in a EFT framework:

$$\mathcal{L} = \boxed{\mathcal{L}^{\mathrm{SM}}} + \boxed{\sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i} + \boxed{\sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j .}$$

SM effective Lagrangian

Gauge boson interactions as described by the SM

Valid below an energy scale Λ

dim-6 : operators describing aTGCs and aQGCs

VBS processes not really competitive for their constraint

dim-8 : lowest order operators describing only aQGCs

Can be constrained by VBS

arXiv:1310.6708v1 [hep-ph] 24 Oct 2013

VBS: Quartic Gauge boson Couplings (QGC)

- Three different types of parameters:

$$\begin{aligned}
\mathcal{L}_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \\
\mathcal{L}_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \\
\mathcal{L}_{T,3} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu} \\
\mathcal{L}_{T,4} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu} \\
\mathcal{L}_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \\
\mathcal{L}_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}
\end{aligned}$$

$$\boxed{\begin{aligned}
\mathcal{L}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}}$$

pure field-strength tensor (f_T) pure transverse

only neutral couplings can be induced

$$\begin{aligned}
\mathcal{L}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \\
\mathcal{L}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \\
\mathcal{L}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \\
\mathcal{L}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned}$$

mixted Higgs-field-strength (f_M)
mixed longitudinal-transverse

$$\boxed{\begin{aligned}
\mathcal{L}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{L}_{S,1} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]
\end{aligned}}$$

pure Higgs field (f_S) pure longitudinal

cannot induce couplings with photons

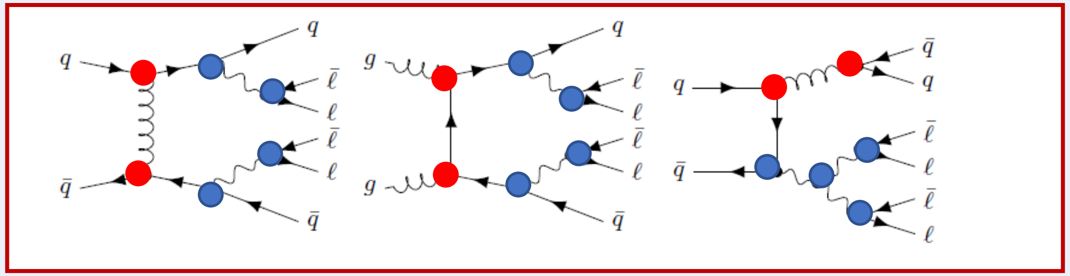
VVjj final state	ZZ	Zγ γγ	W^+W^- WZ	$W^\pm W^\pm$	Wγ
$f_{S,0}$, $f_{S,1}$	✔		✔	✔	
$f_{M,0}$, $f_{M,1}$, $f_{M,6}$, $f_{M,7}$	✔	✔	✔	✔	✔
$f_{M,2}$, $f_{M,3}$, $f_{M,4}$, $f_{M,5}$	✔	✔	✔		✔
$f_{T,0}$, $f_{T,1}$, $f_{T,2}$	✔	✔	✔	✔	✔
$f_{T,5}$, $f_{T,6}$, $f_{T,7}$	✔	✔	✔		✔
$f_{T,8}$, $f_{T,9}$	✔	✔			

VBS: a challenging process

α_{EW} order: 4
α_s order: 2

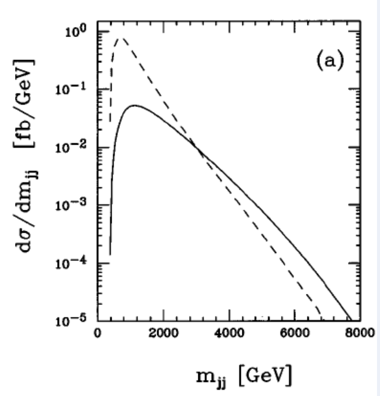
QCD diboson production in association with two jets

- Very high background for most channels

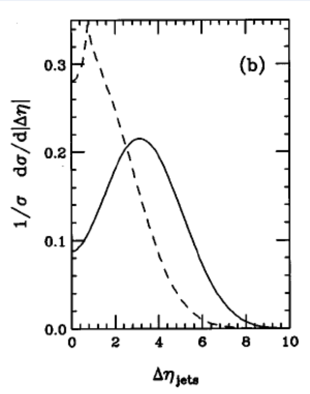


EW diboson production: very characteristic kinematic signature

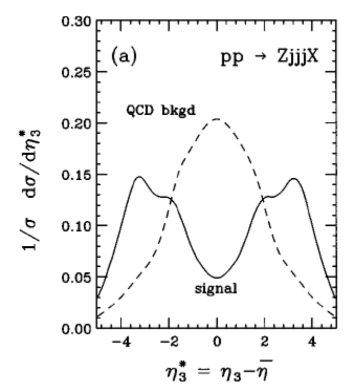
typically m_{jj}>500 GeV in VBS analyses



dijet invariant mass



dijet Δη



centrality

arXiv:hep-ph/9605444

Same final state as EW: $|MINC|^2 = |M_{QCD} + M_{EW}|^2 = |M_{QCD}|^2 + |M_{EW}|^2 + 2\times Re\left(M_{QCD}{}^{*}\times M_{EW}\right)$

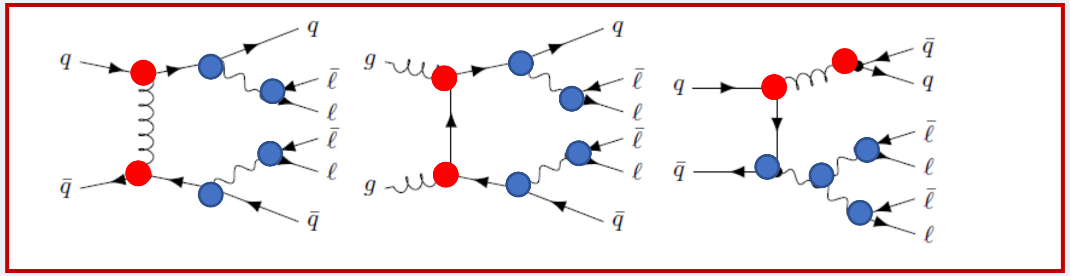
Interference term: Taken into account as shape uncertainty in most analyses

VBS: a challenging process

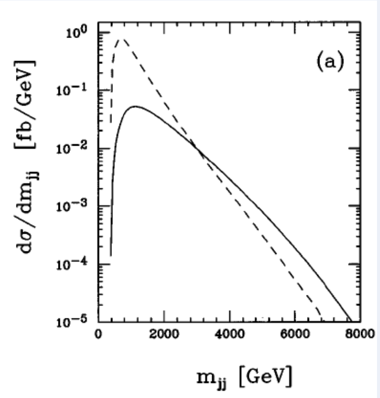
α_{EW} order: 4
α_s order: 2

QCD diboson production in association with two jets

- Very high background for most channels

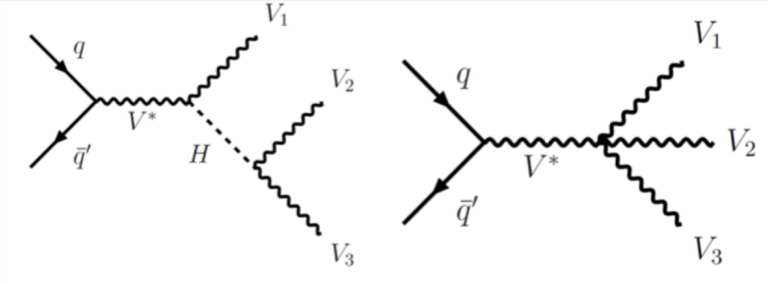


EW diboson production: very characteristic kinematic signature



dijet invariant mass

m_{jj}>150 GeV cut used to supress triboson diagrams:

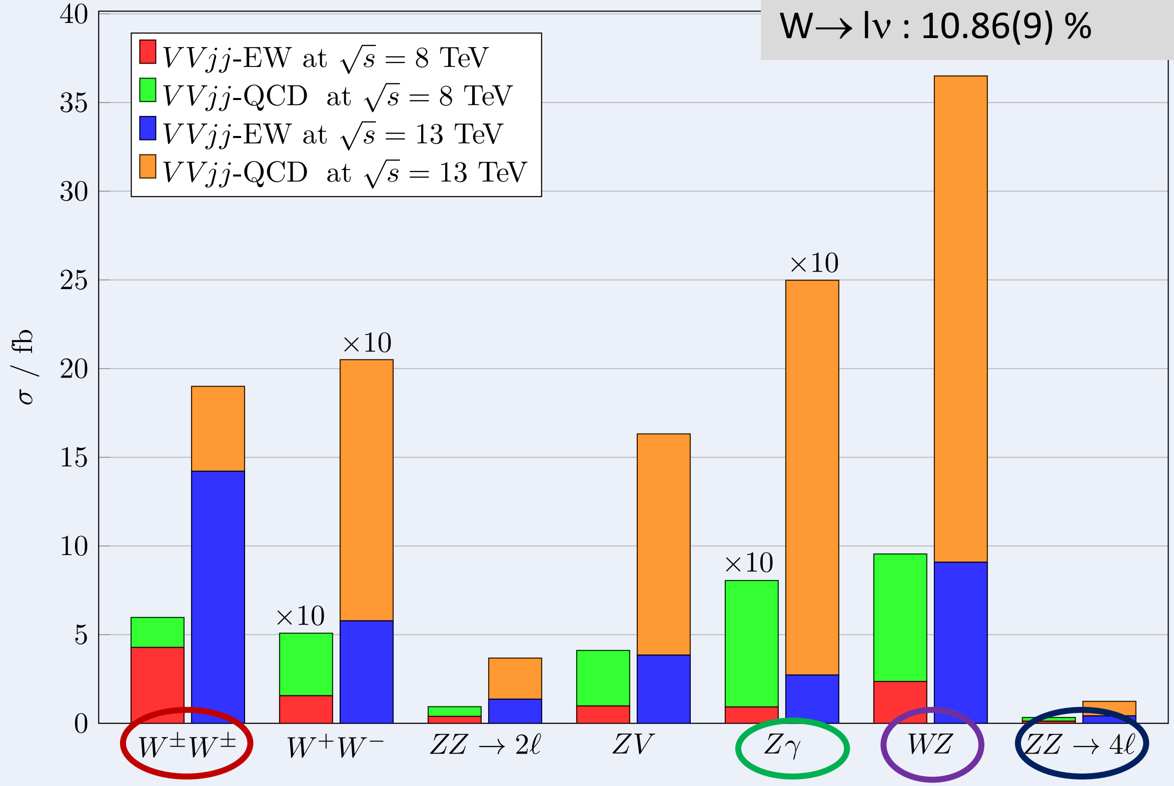


α_s order: 0

VBS: a challenging process

- $W^{\pm}W^{\pm}$: lead to the first observation
  - ✓Suffers from high fake background
- WZ: first observed in 2018
  - ✓Suffers from high QCD background
- ZZ: recent observation
  - ✓Very clear signature but low cross section

Leptonic decays : e & μ
$Z \rightarrow ll$: 3.3658(23) %
$W \rightarrow l\nu$: 10.86(9) %

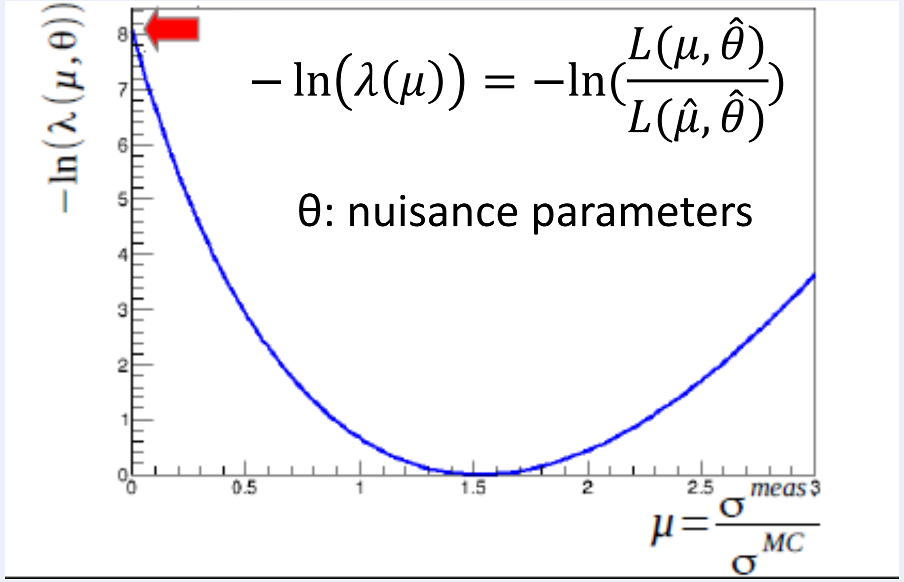


P. Anger CERN-THESIS-2014-105

- Vγ and VV semi-leptonic
  - ✓Challenging but should lead to an observation soon (evidence for Zγ)
  - ✓Important in order to complete the full electroweak production scheme

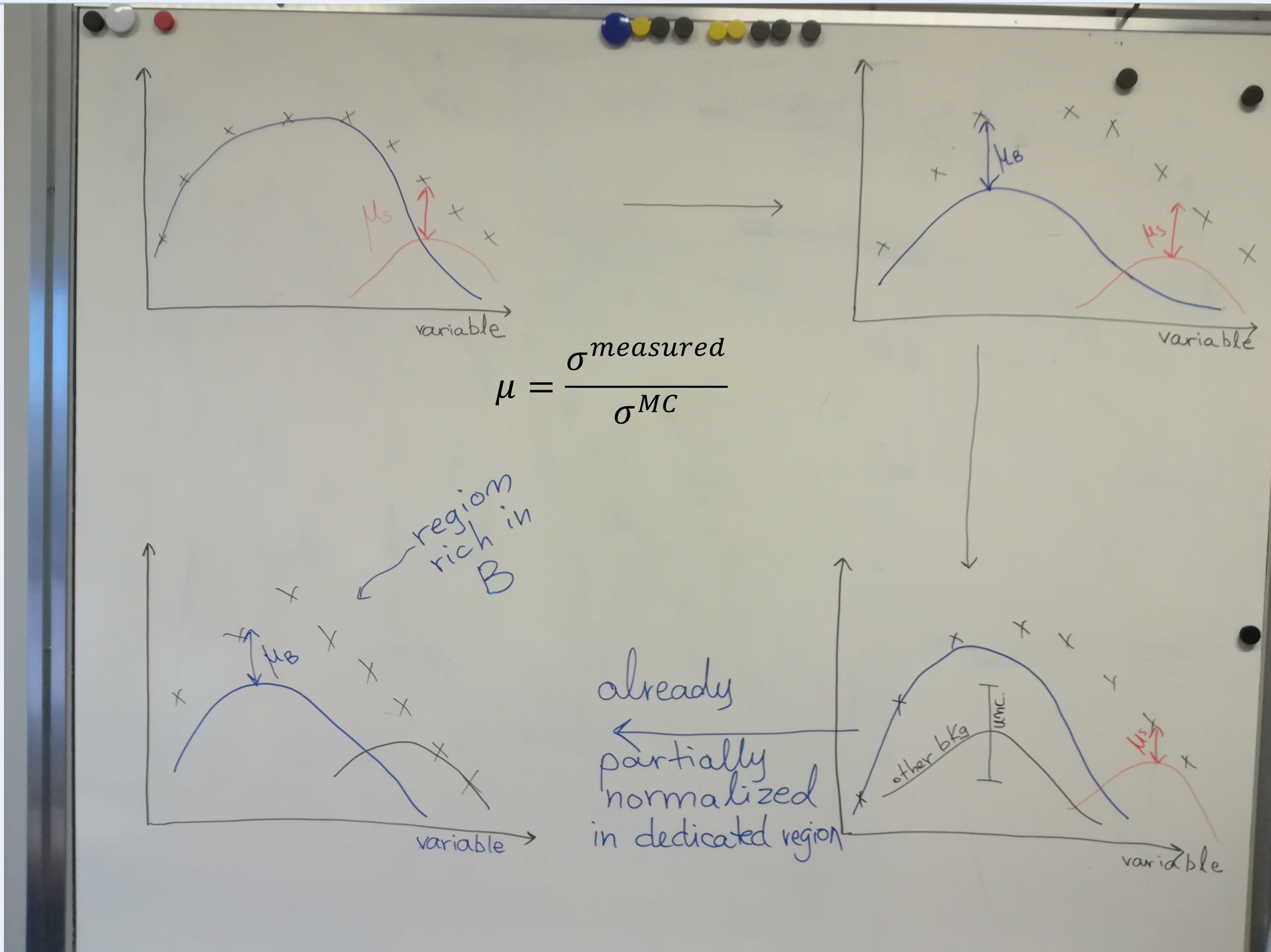
How to extract this low signal?

- VBS searches: generally shape based analysis
- The idea: fit taking advantage from the characteristic VBS topology
- Its minimization directly gives the signal force μ



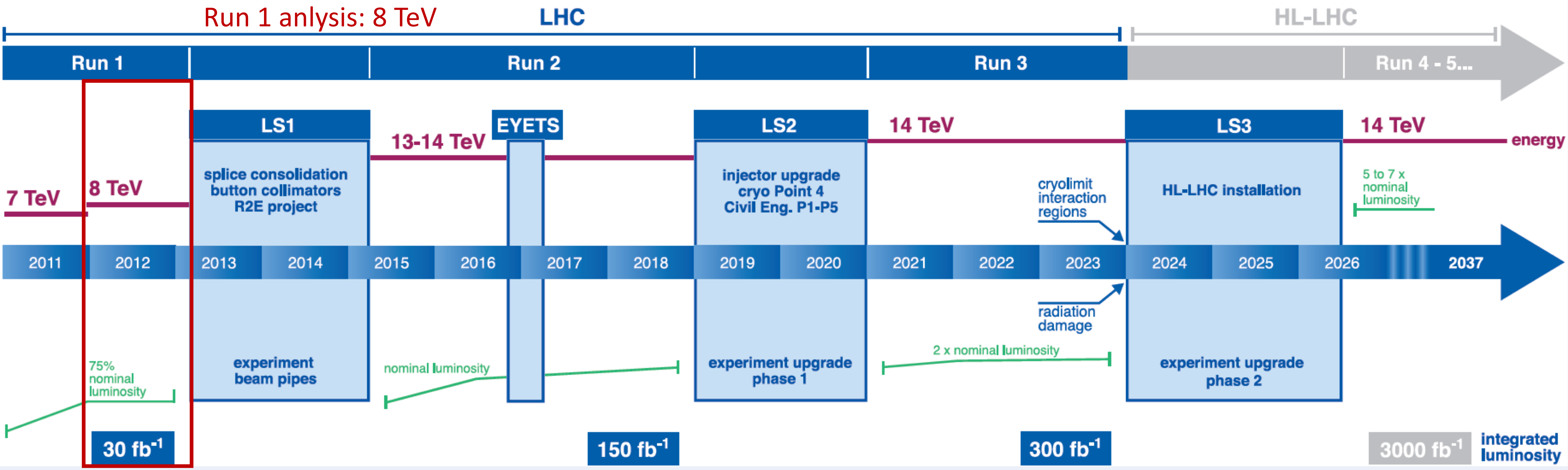
$$-\ln(\lambda(\mu)) = -\ln\left(\frac{L(\mu,\hat{\theta})}{L(\hat{\mu},\hat{\theta})}\right)$$

θ: nuisance parameters



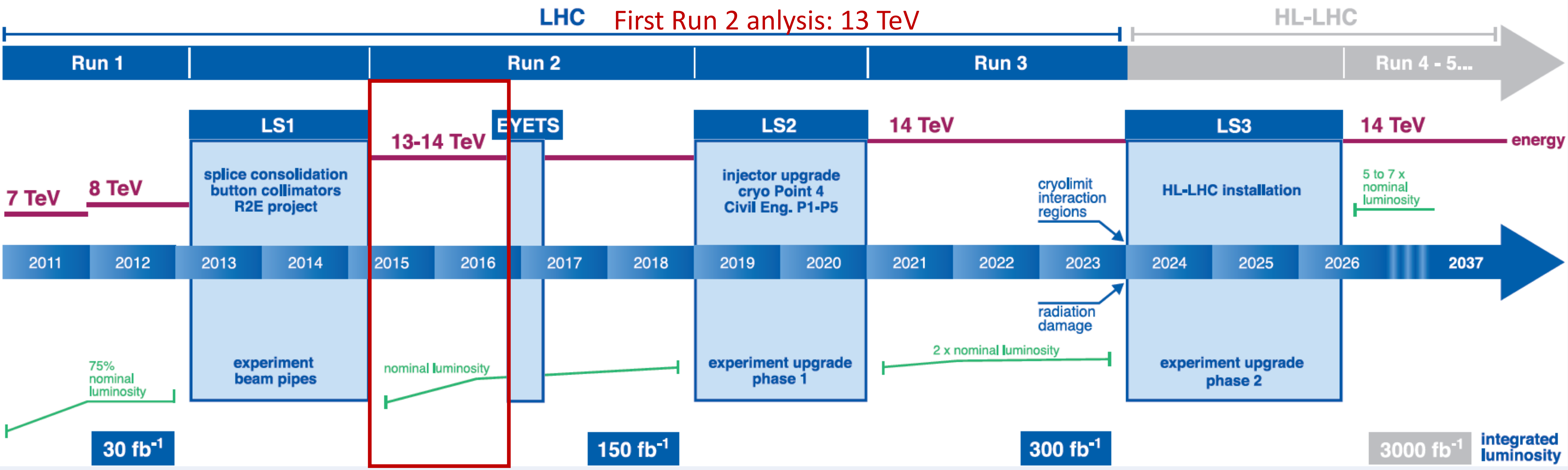
$$\mu = \frac{\sigma^{measured}}{\sigma^{MC}}$$

Vector Boson Scattering: timeline



- No observation of the pure electroweak production were possible
- Both experiments built the strategy of constraining aQGCs

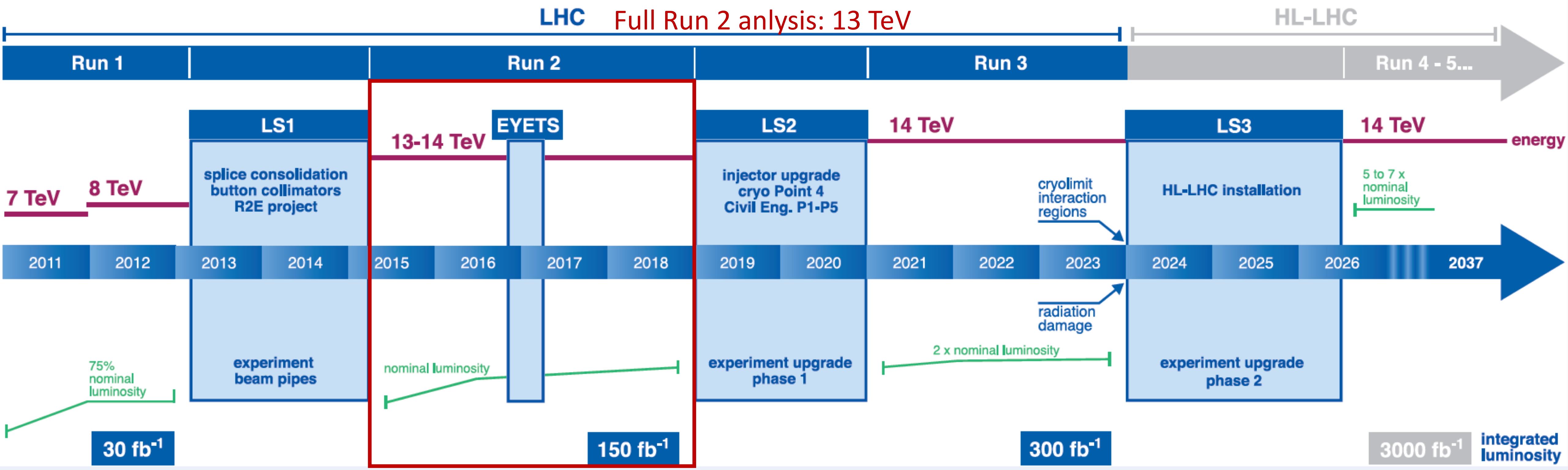
Vector Boson Scattering: timeline



First Run 2 anlysis: 13 TeV

- First observation of the electroweak $W^{\pm}W^{\pm}jj$ production by both ATLAS and CMS
- First observation of the electroweak WZjj production by ATLAS

Vector Boson Scattering: timeline



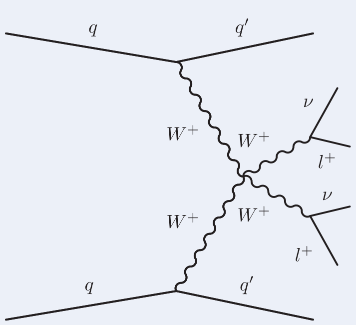
- First observation of the electroweak ZZjj production by ATLAS
- Almost every other channel analysis still in progress…

$W^{\pm}W^{\pm}jj$ channel

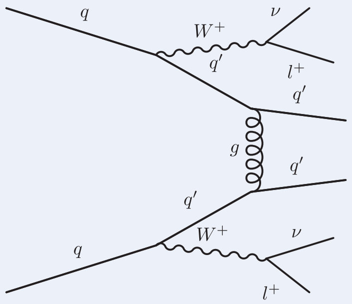
Best EW/QCD ratio channel

Selection:

- Exactly two same sign leptons and E_T^{miss}
- At least two high P_T forward jets



ssWW EW



ssWW QCD: very low

Suffering from **high fake background**

- **Non prompt leptons**
- Electron charge misidentification

- Important background from WZ QCD

First EW diboson production observation by CMS

Observation both by ATLAS and CMS:

ATLAS: PRL 123 (2019) 161801
CMS: PRL 120 (2018) 081801

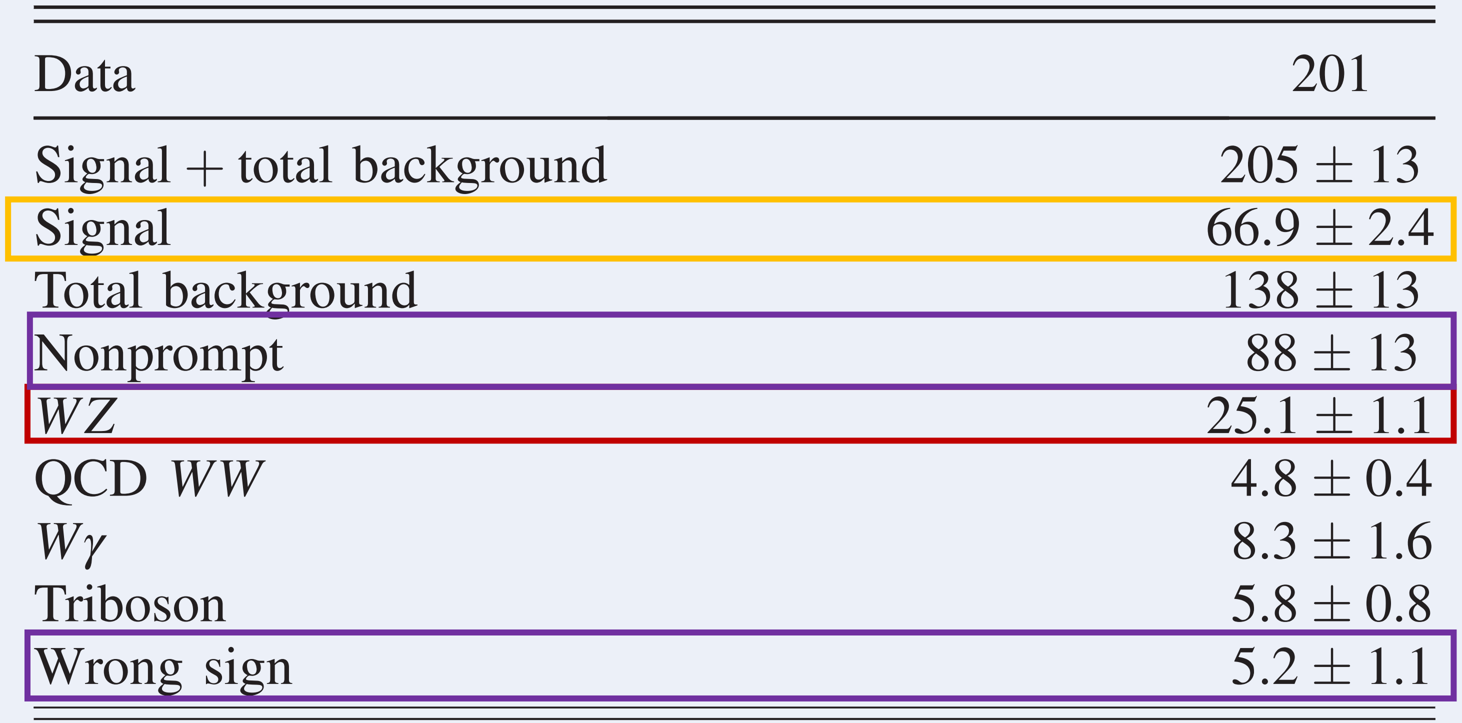
Event yields and background estimation

- Different phase space for the cross section measurement:

2 same sign leptons and E_T^{miss}
2 jets: m_{jj}>500 GeV *for both*
Centrality: *only constrained for CMS*

- Signal modelling and background estimation:

CMS



Data	201
Signal + total background	205 ± 13
Signal	66.9 ± 2.4
Total background	138 ± 13
Nonprompt	88 ± 13
WZ	25.1 ± 1.1
QCD *WW*	4.8 ± 0.4
$W\gamma$	8.3 ± 1.6
Triboson	5.8 ± 0.8
Wrong sign	5.2 ± 1.1

Signal: simulated in LO
(MadGraph5 aMC@NLO2.3.3: LO EWK, LO QCD)

Reducible background: extracted from data

normalized using data, in dedicated control region

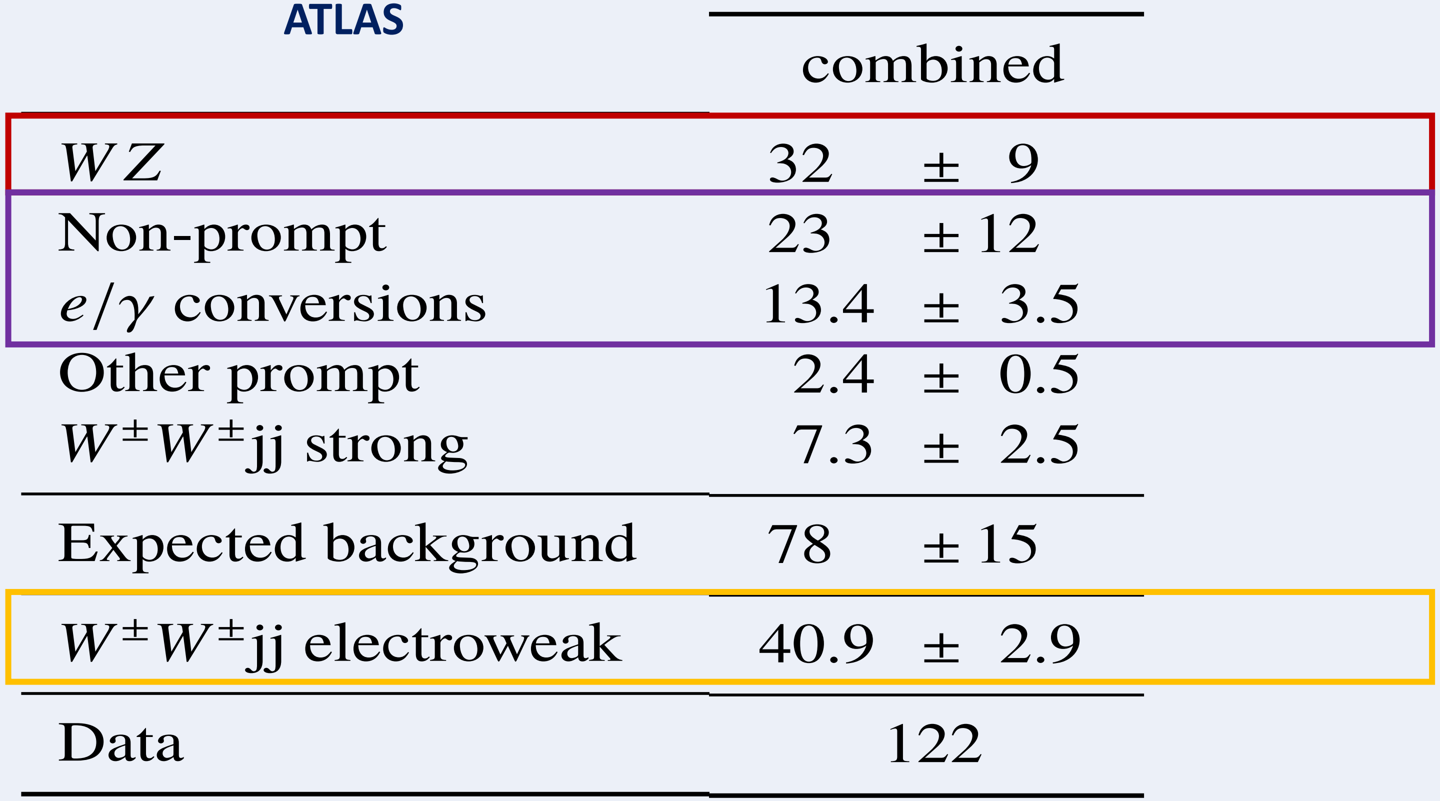
Event yields and background estimation

- Different phase space for the cross section measurement:

2 same sign leptons and E_T^{miss}
2 jets: ***m_{jj}>500 GeV*** *for both*
Centrality: *only constrained for CMS*

- Signal modelling and background estimation:

ATLAS



	combined
WZ	32 ± 9
Non-prompt	23 ± 12
e/γ conversions	13.4 ± 3.5
Other prompt	2.4 ± 0.5
$W^\pm W^\pm$jj strong	7.3 ± 2.5
Expected background	78 ± 15
$W^\pm W^\pm$jj electroweak	40.9 ± 2.9
Data	122

Signal: simulated in LO
(Sherpa2.2.2, LO EWK, 2,3j@LO QCD)

Reducible background: extracted from data

normalized using data, in dedicated control region

CMS analysis strategy and results

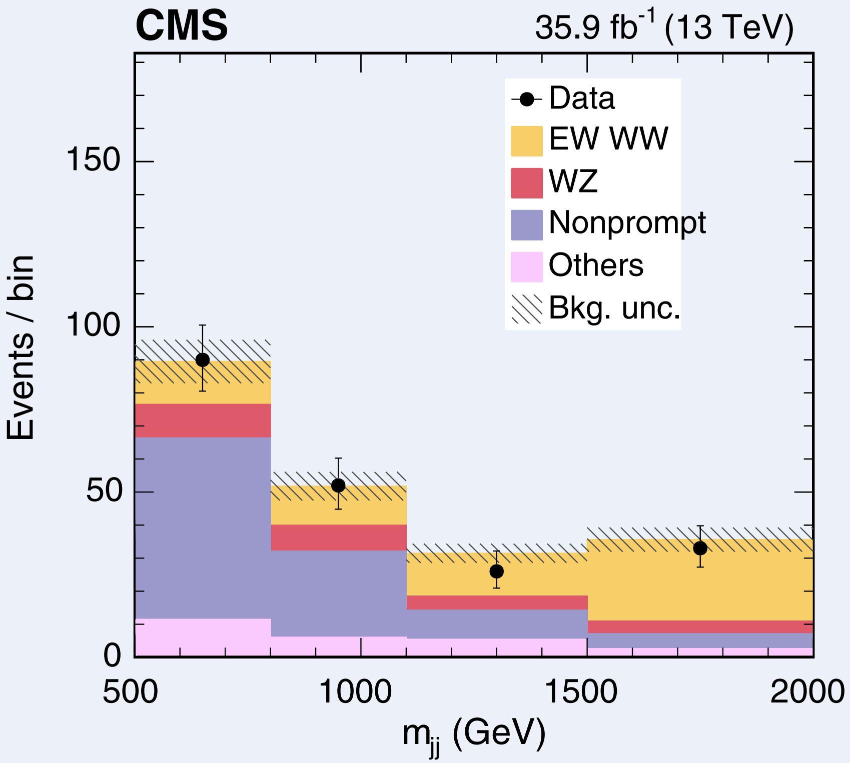
- Signal extraction:

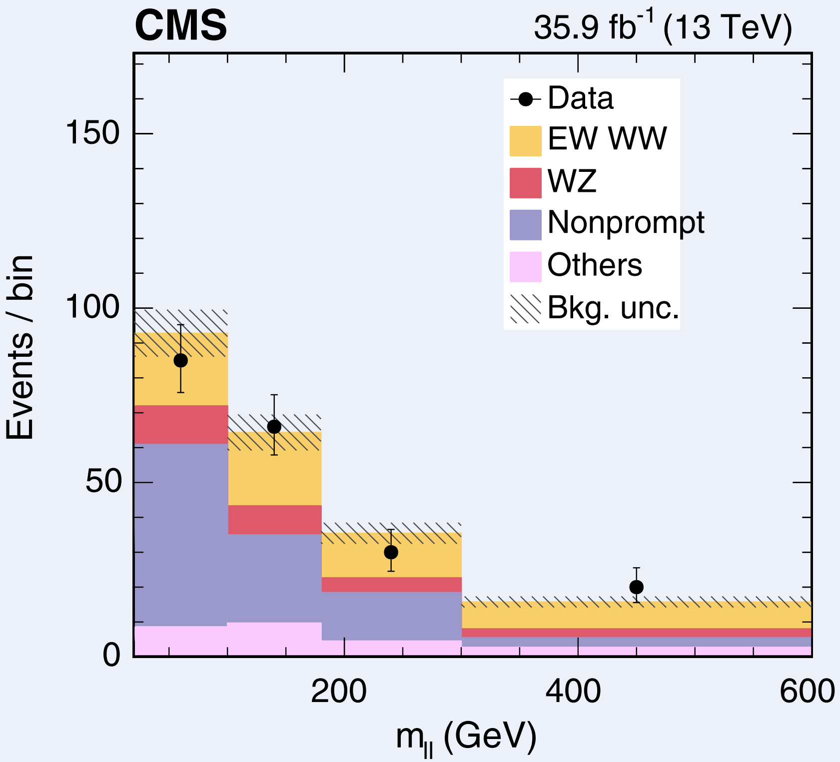
with a 2D template fit

using m_{ll} and m_{jj}

simultaneously with WZ CR

5.5 σ observation (5.7 expected)





- Fiducial cross section measurement:

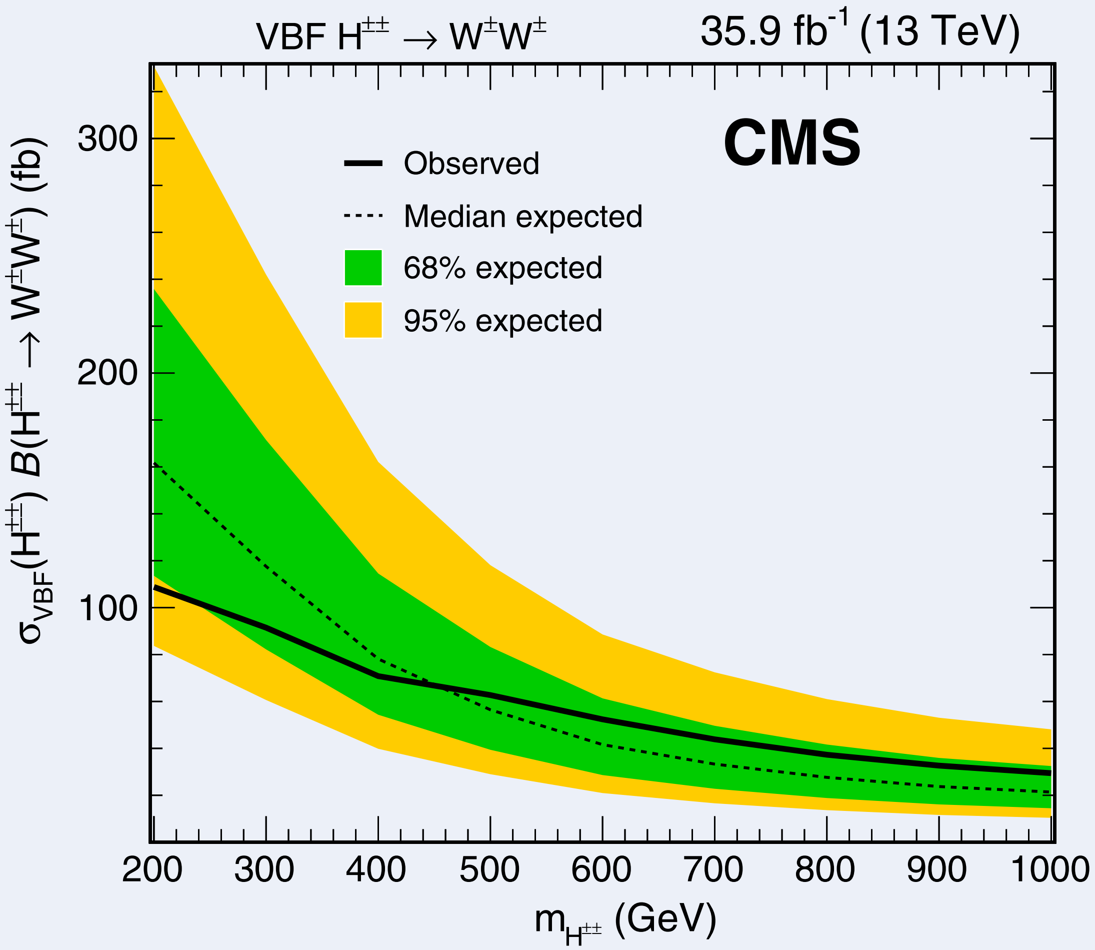
$$\sigma_{\text{fid}}(W^{\pm}W^{\pm}jj) = \quad 3.83 \pm 0.66\,(\text{stat}) \pm 0.35\,(\text{syst})\ \text{fb}$$

CMS analysis strategy and results

- Limits on

in a Georgi-Machacek model of Higgs triplets predicting doubly charged Higgs bosons

$$\sigma_{\mathrm{VBF}}(H^{\pm\pm})\mathcal{B}(H^{\pm\pm} \to W^{\pm}W^{\pm})$$



ATLAS analysis strategy and results

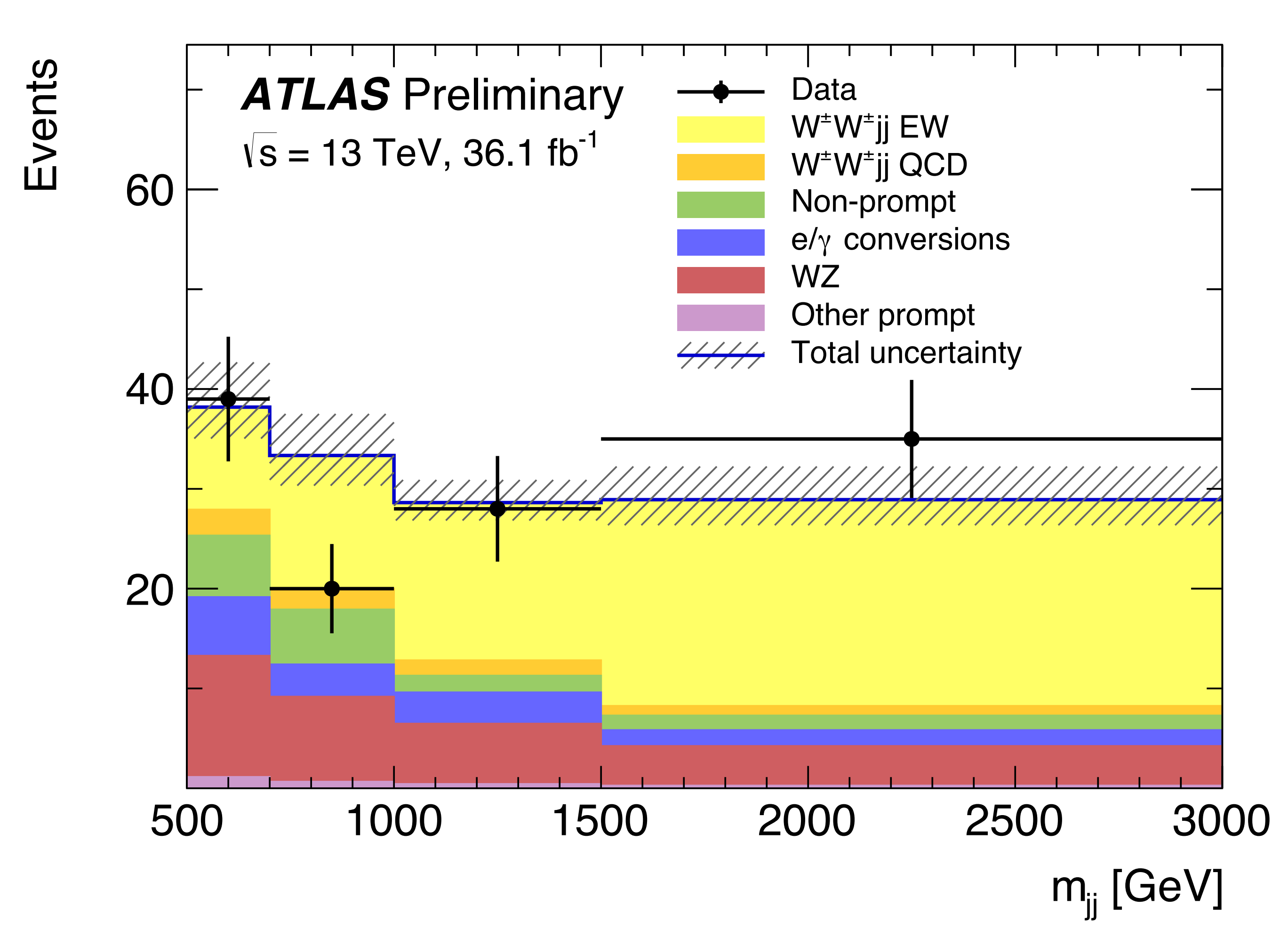
- Signal extraction:

with a 1D template fit using m_{jj} in 6 categories simultaneously with WZ and non-prompt CR

6.9 σ observation (4.25 expected)

- Fiducial cross section measurement:

$$\sigma^{\text{fid}} = 2.91^{+0.51}_{-0.47}\ (\text{stat.}) \pm 0.27\ (\text{sys.})\ \text{fb}$$



WZ jj channel

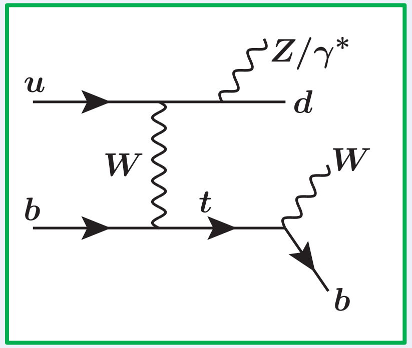
Low fake background

Selection:

- Exactly 3 leptons

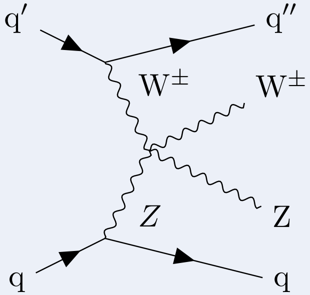
(among those 1 opposite sign but same flavor pair)

- At least two high P_T forward jets
- b-jet veto to suppress:

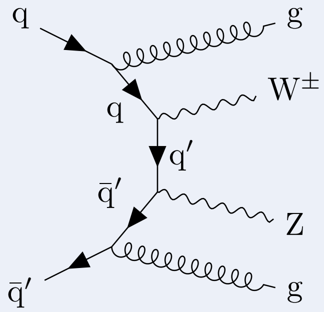


Low EW/QCD ratio channel

- Need to discriminate the signal using MV technics



WZ EW



WZ QCD: $\frac{EW}{QCD} < 0.5$

in a typical VBS SR

Observation by ATLAS
PLB 793 (2019) 469

aGCS limits by CMS
PLB 795 (2019) 281

Event yields and background estimation

- Different phase space for the cross section measurement:

- Signal modelling and background estimation:

CMS

Process	Total yield
QCD WZ	34.1 ± 1.1
t+V/VVV	12.9 ± 0.5
Nonprompt	9.9 ± 2.3
VV	3.5 ± 0.2
$Z\gamma$	2.1 ± 0.8
Pred. background	62.4 ± 2.8
EW WZ signal	15.1 ± 1.6
Data	75

3 leptons
Constraint on P_T^{miss} for CMS, on m_T^W for ATLAS
2 jets: ***m_{jj}>500 GeV*** *for both*
Centrality: *only constrained for CMS*
b-jet veto for both

Signal: simulated in LO
(MadGraph5 aMC@NLO2.4.2, LO EWK, LO QCD)

Reducible background: extracted from data

Irreducible background: simulated in LO
(MadGraph5 aMC@NLO2.4.2: LO with up to 3 partons at Born level)
normalized using data, in dedicated control region

Event yields and background estimation

- Different phase space for the cross section measurement:

3 leptons
Constraint on P_T^{miss} for CMS, on m_T^W for ATLAS
***2 jets:** **m_{jj}>500 GeV** for both*
***Centrality:** only constrained for CMS*
b-jet veto for both

- Signal modelling and background estimation:

ATLAS

	SR
Data	161
Total predicted	167 ± 11
$WZjj$–EW (signal)	44 ± 11
$WZjj$–QCD	91 ± 10
Misid. leptons	7.8 ± 3.2
$ZZjj$–QCD	11.1 ± 2.8
tZj	6.2 ± 1.1
$t\bar{t}+V$	4.7 ± 1.0
$ZZjj$–EW	1.80 ± 0.45
VVV	0.59 ± 0.15

Signal: simulated in LO
(Sherpa2.2.2, LO EWK, 2,3j@LO)

Reducible background: extracted from data

Irreducible background: simulated in LO
(Sherpa2.2.2, up to 1j@ NLO + 2,3j@LO)
normalized using data, in dedicated control region

Normalized in dedicated CR

CMS analysis strategy and results

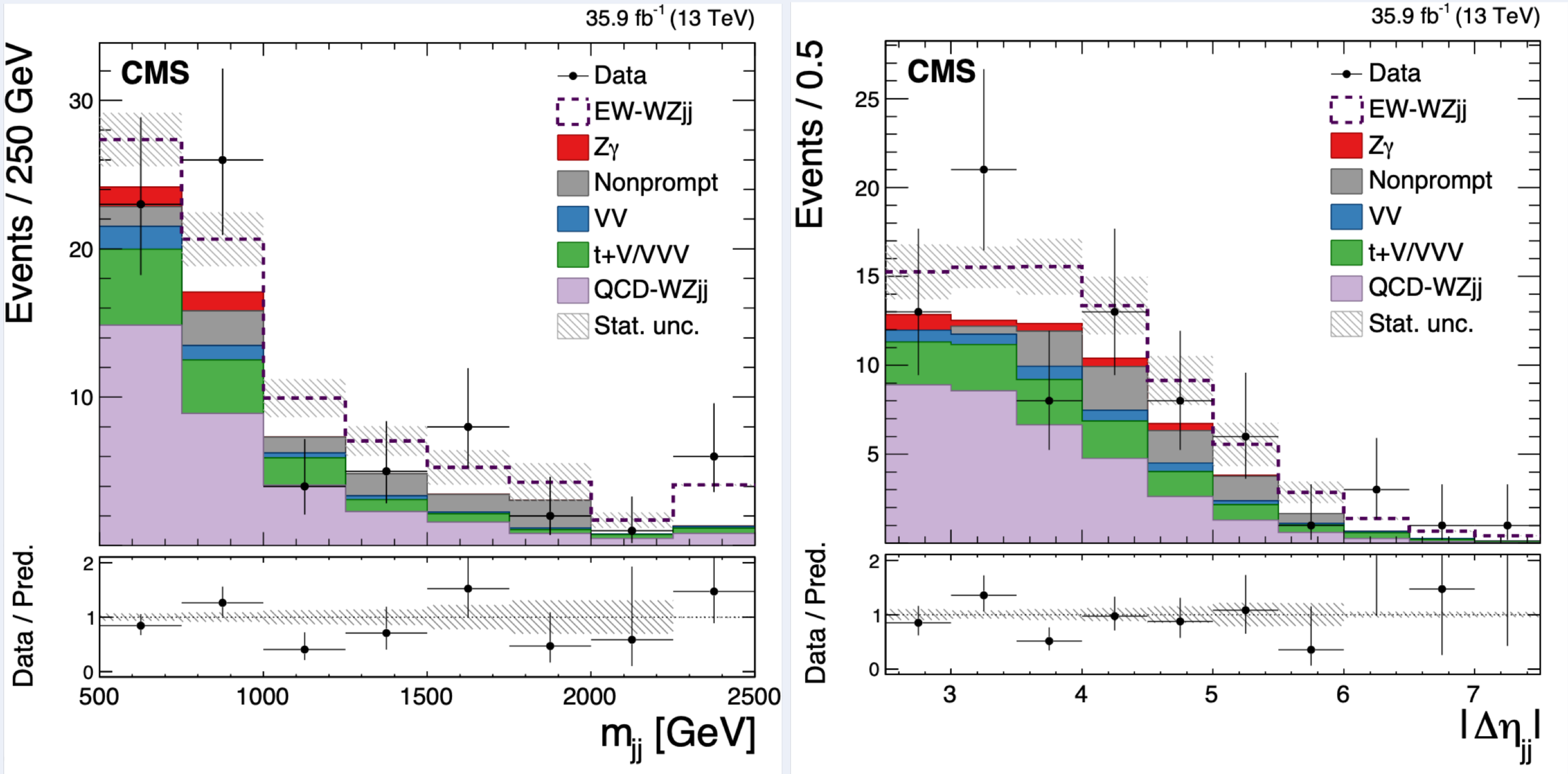
- Signal extraction:

with a 2D template fit

using $|\Delta\eta_{jj}|$ and m_{jj}

simultaneously with QCD CR

2.2 σ (2.5 expected)



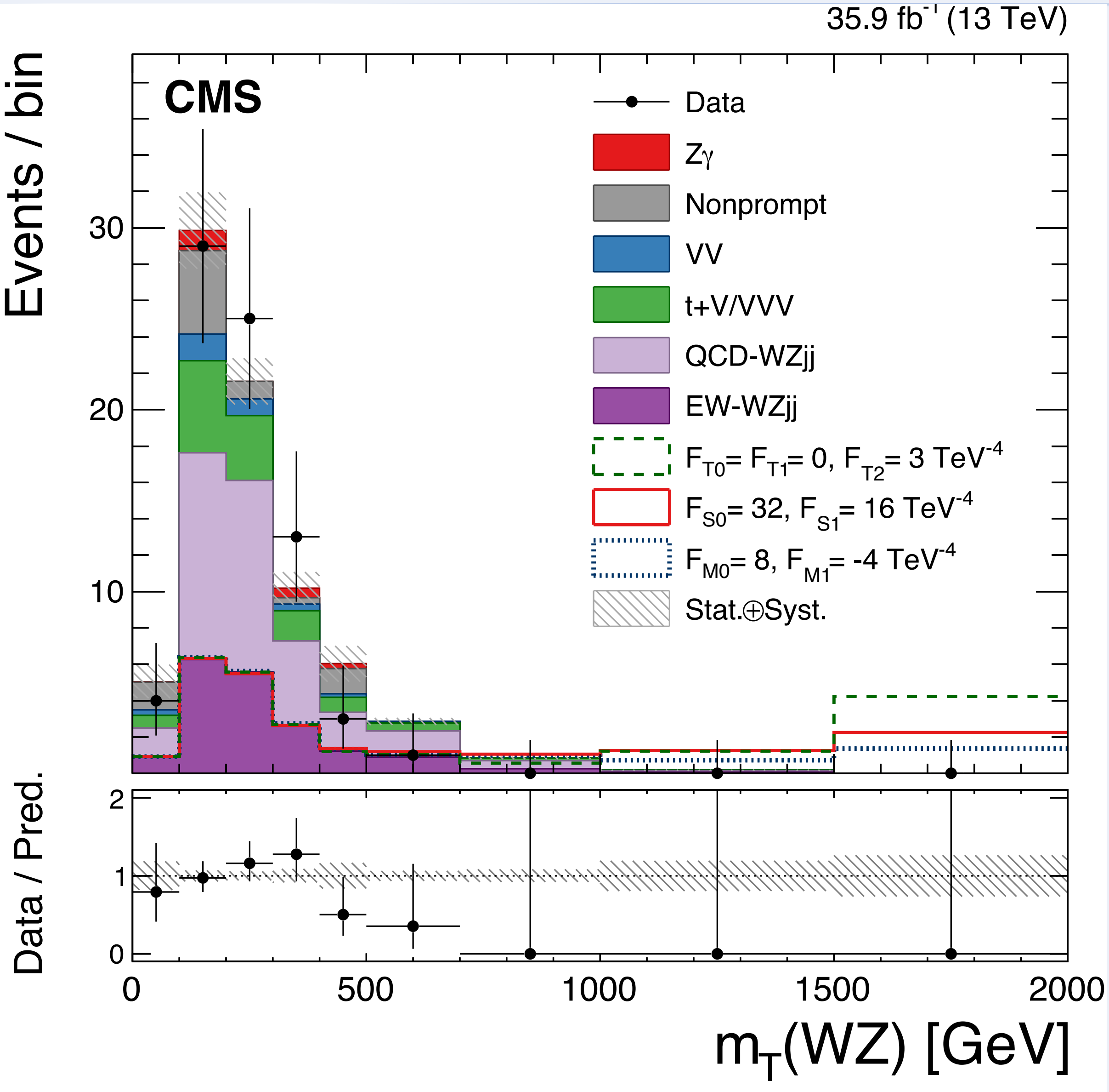
CMS: interpretation studies

- No evidence of WZjj EW production

BUT

- Channel used to constraint BSM scenarios

- The transverse mass of the diboson system very sensitive to new physics

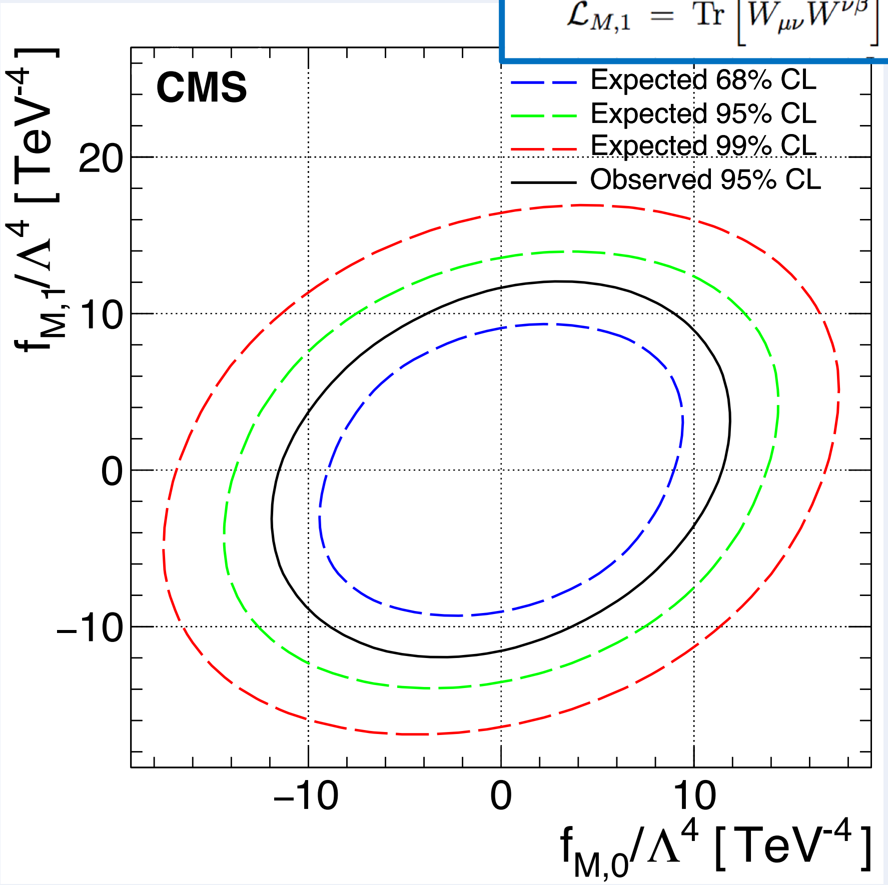


CMS: interpretation studies

- Limits on aQGC using m_T^{WZ} distribution:

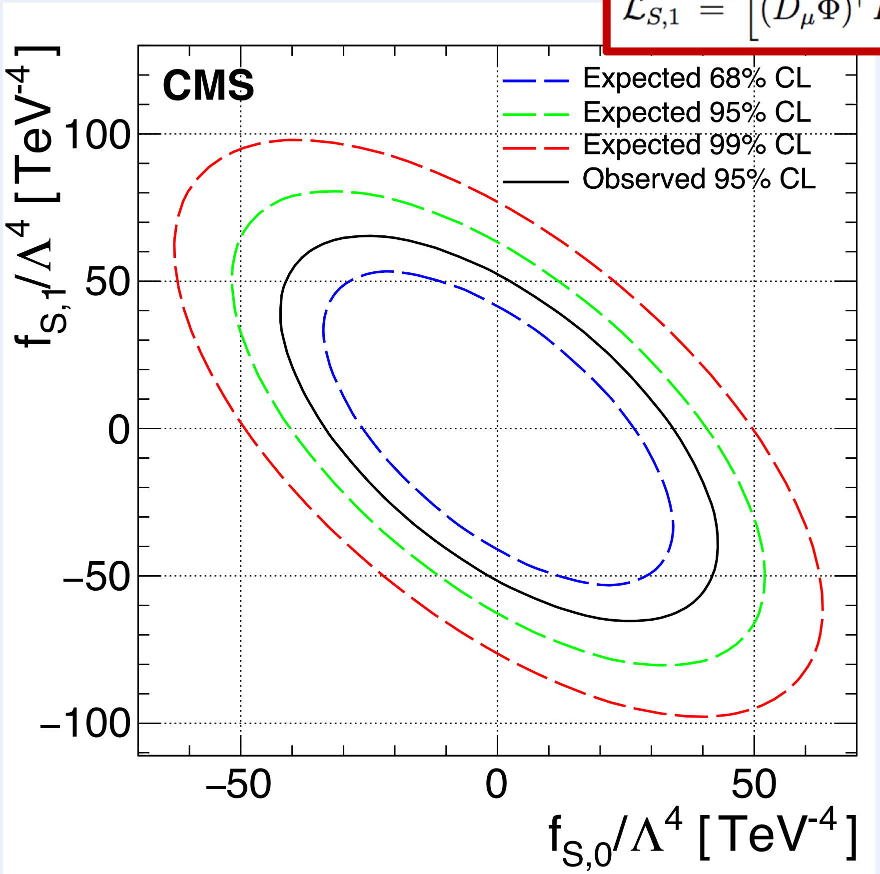
$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$



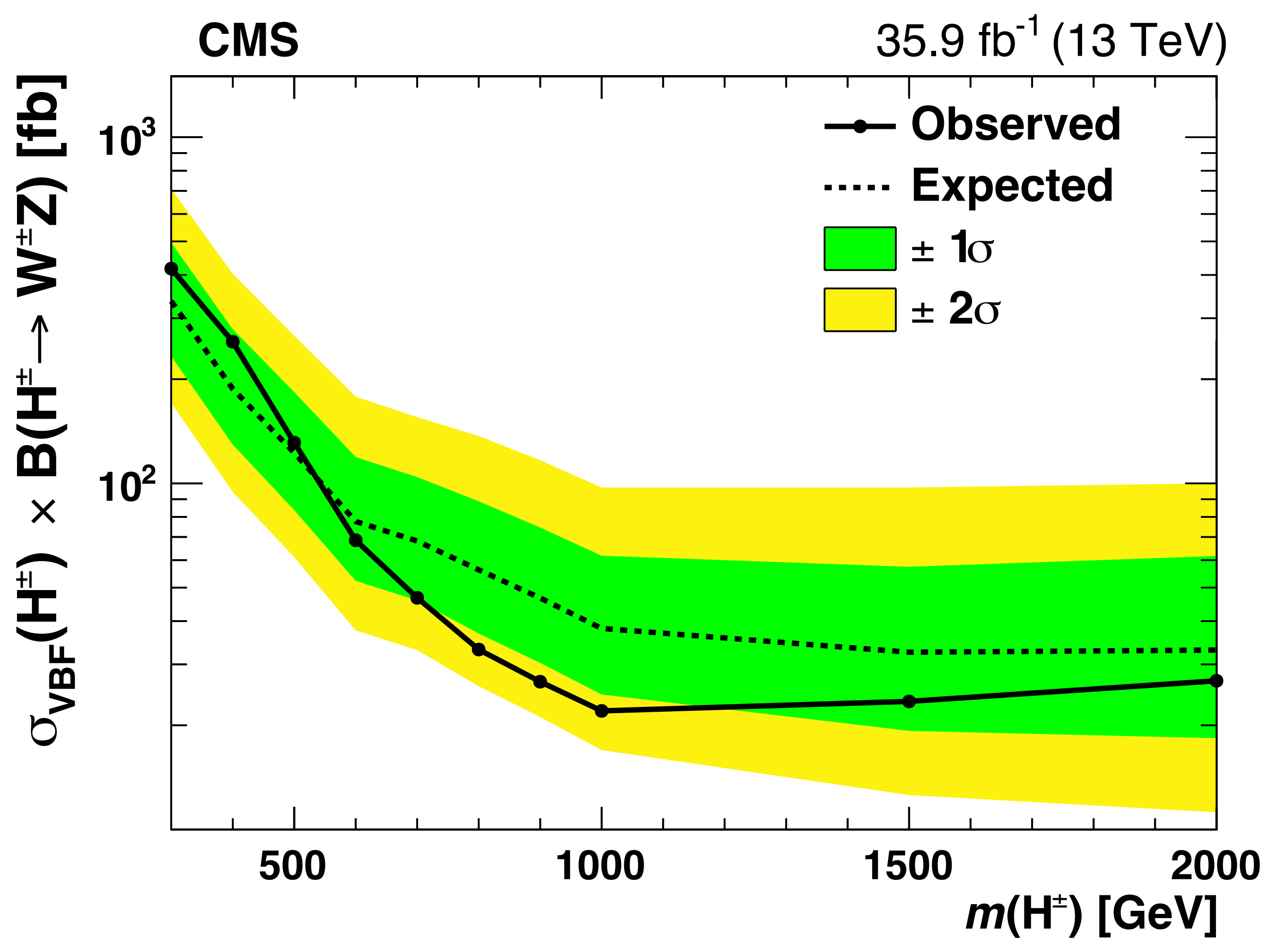
$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$



CMS: interpretation studies

- Limits on $\sigma(\mathrm{H}^{\pm})\,\mathcal{B}(H^{+} \rightarrow \mathrm{WZ})$ (Georgi-Machacek model predicting enhanced coupling with bosons)



combined fit of EW+QCD in the SR
and QCD in the QCD CR

ATLAS analysis strategy and results

$\Delta y(\ell_W, Z)$	m_{jj}	η_W
ζ	$\Delta R(j1, Z)$	p_T^{j2}
$R_{p_T^{hard}}$	$\Delta\eta(j1, j2)$	p_T^{j1}
N_{jets}	p_T^W	m_T^{WZ}
$\Delta\phi(j1, j2)$	η_{j1}	p_T^Z

- Signal extraction:

with a 1D template fit using Boosted Decision Tree score

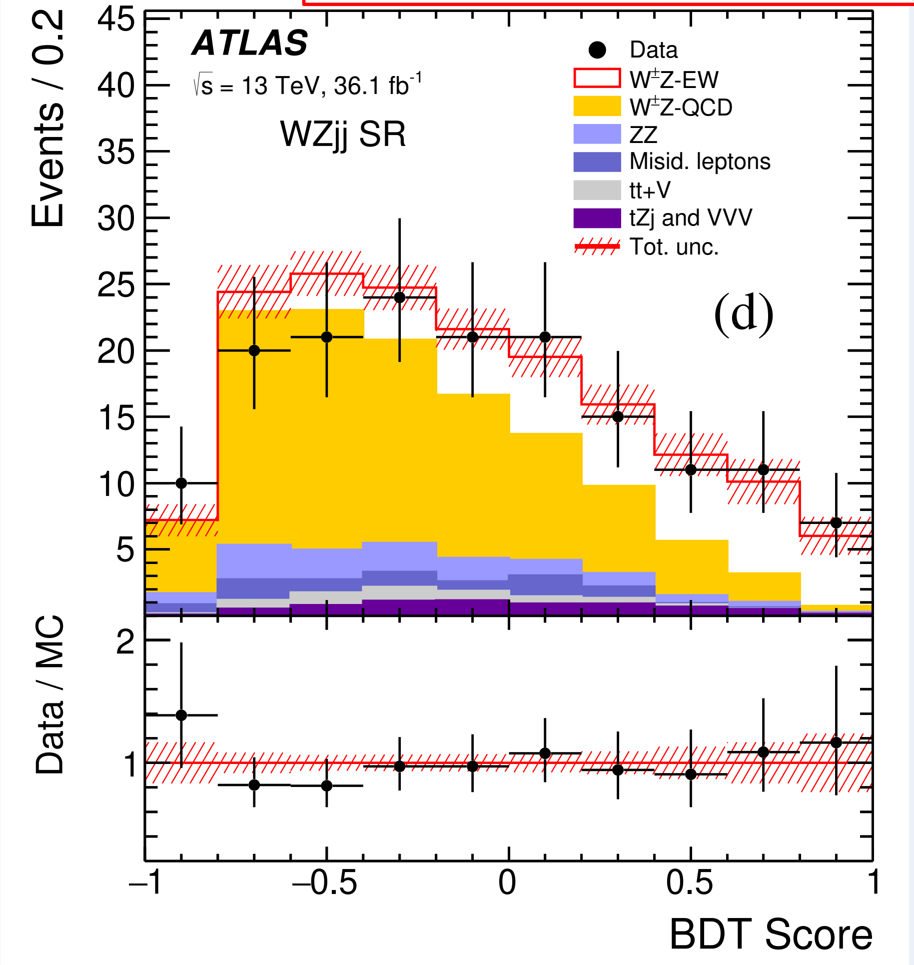
simultaneously with QCD CR, b-CR and ZZ-CR

invert M_{jj}>500 GeV

invert b-jet veto

invert third lepton veto

5.3 σ observation (3.2 expected)



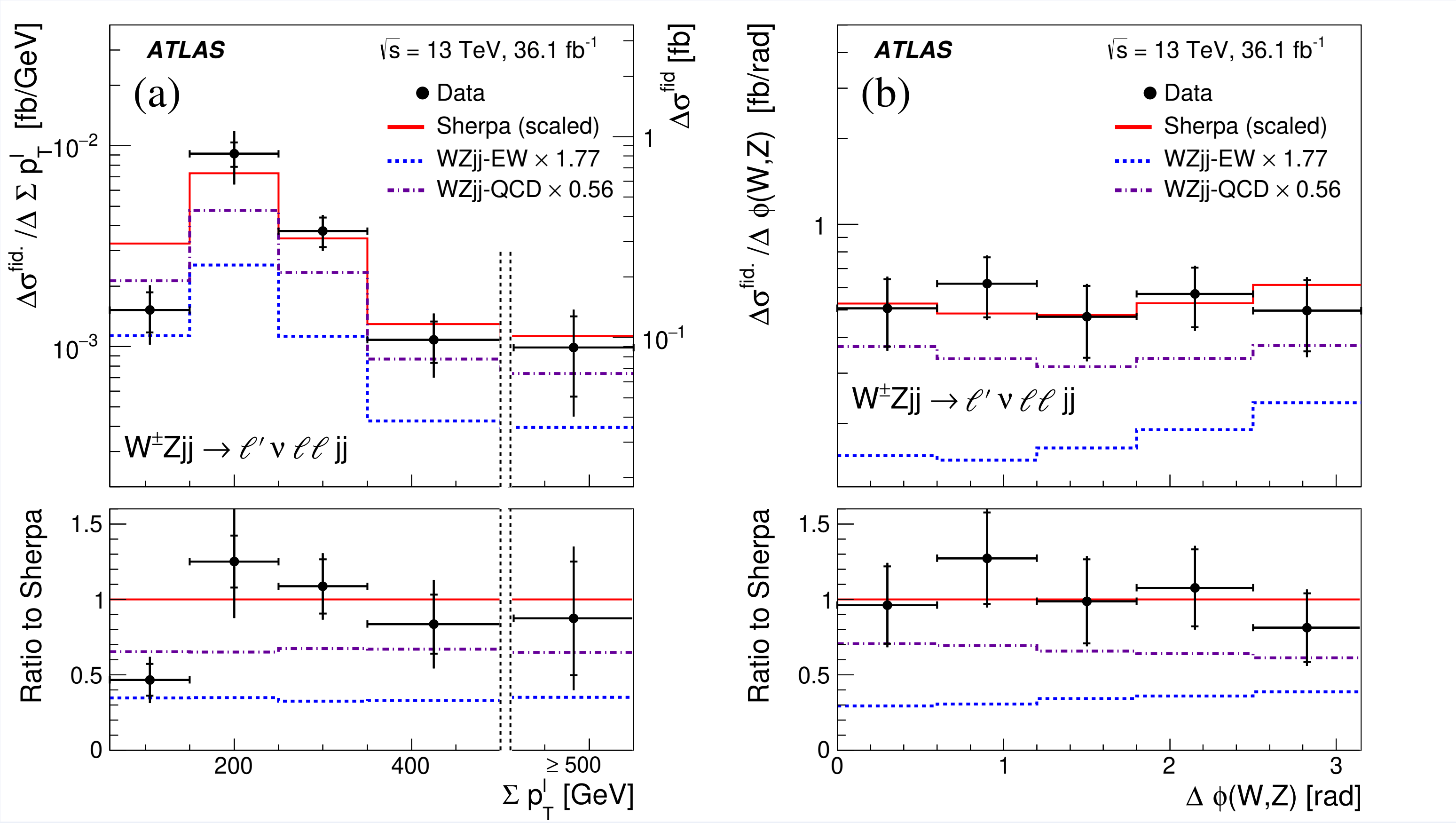
- Fiducial cross section measurement:

$$\sigma^{\text{fid.}}_{WZjj-\text{EW}} = 0.57\,^{+0.14}_{-0.13}\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp. syst.})\,^{+0.05}_{-0.04}\,(\text{mod. syst.})\,^{+0.01}_{-0.01}\,(\text{lumi.})\ \text{fb}$$

ATLAS analysis strategy and results

- QCD+EW fiducial cross section measurement: $\sigma^{\text{fid.}}_{W^{\pm}Zjj} \quad = \quad 68 \pm 0.25 \text{ fb}$

- Differential cross section measurement (QCD and EW)



Sensible to aQGCs:
m_T^{WZ}, $\sum p_T^{l}$, $\Delta\phi(W,Z)$

Jets modelling in MC :
N_{jets}, M_{jj}, $\Delta\phi(j_1,j_2)$, $\Delta y(j_1,j_2)$, N_{jets}^{gap}

Input to theorists!!

ZZ jj channel

Low fake background

- Exactly 2 pairs leptons

(opposite sign but same flavor pairs)

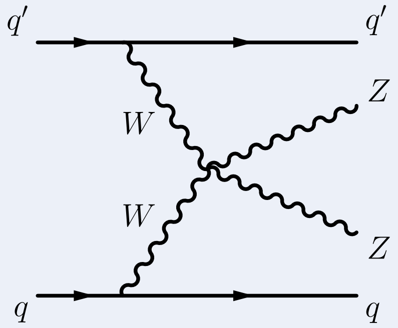
- Or: 1 lepton pair and E_T^{miss}

(opposite sign but same flavor pair)

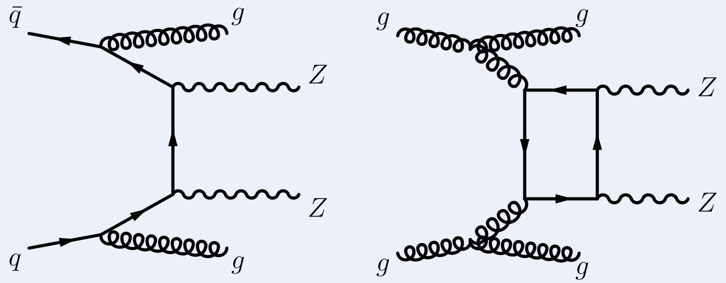
- At least two high P_T forward jets

Low cross section and EW/QCD ratio channel

- Need to discriminate the signal using MV technics



WZ EW



WZ QCD: $\frac{EW}{QCD} \sim 0.3$ *in the VBS SR*

CMS:
PLB 774 (2017) 682
(only 2015-2016, no observation)

ATLAS:
ATLAS-CONF-2019-033
EPS-HEP 2019 Ghent, Belgium, 10 - 17 July 2019

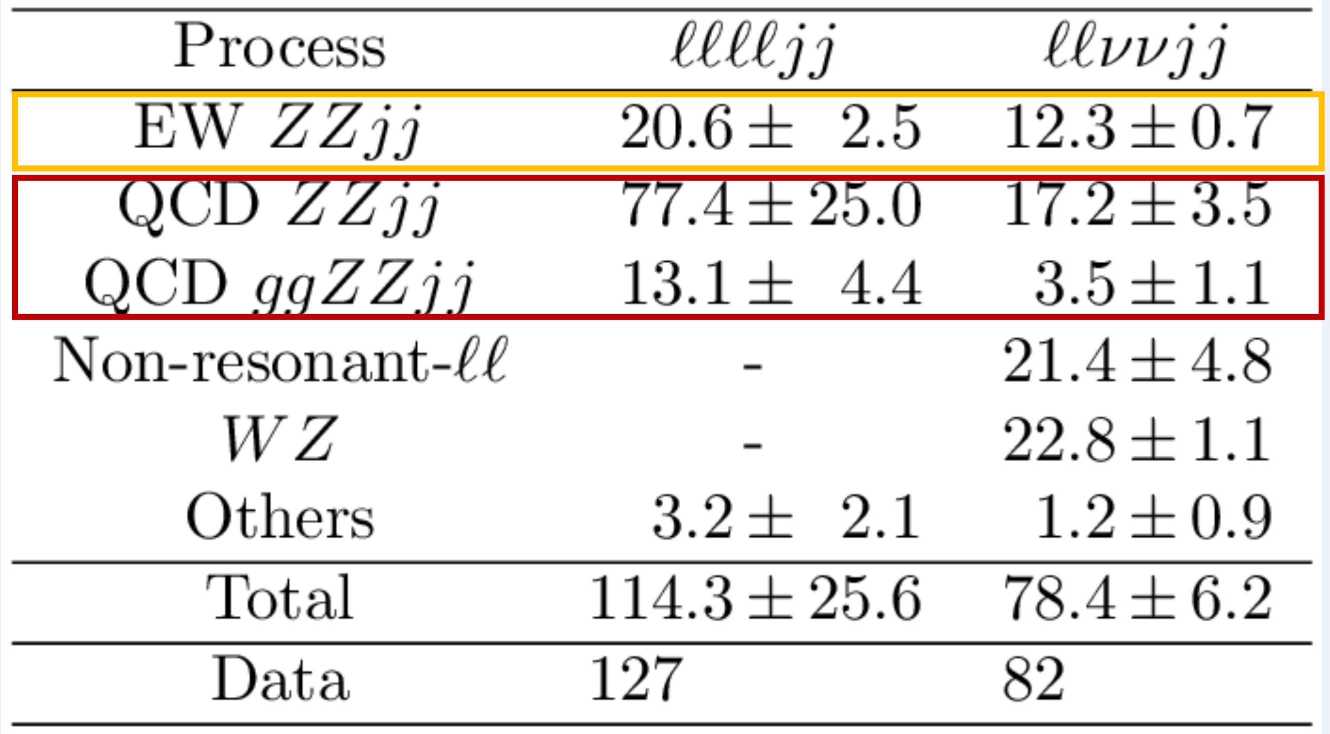
Event yields and background estimation

- Different phase space for the cross section measurement:

4 leptons or 2 leptonos and constraint on E_T^{miss}
2 jets: ***m_{jj}>300 GeV*** *for llll,* ***m_{jj}>400 GeV*** *for llvv*

- Signal modelling and background estimation:

ATLAS



Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.3 ± 0.7
QCD $ZZjj$	77.4 ± 25.0	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114.3 ± 25.6	78.4 ± 6.2
Data	127	82

Signal: simulated in LO
(MadGraph5_aMC@NLO 2.6.1)

Irreducible background:
(Sherpa2.2.2 for both ZZjj and ggZZjj, up to one (three) outgoing partons are generated at NLO (LO))
normalized using data, in dedicated control region

ATLAS analysis strategy and results

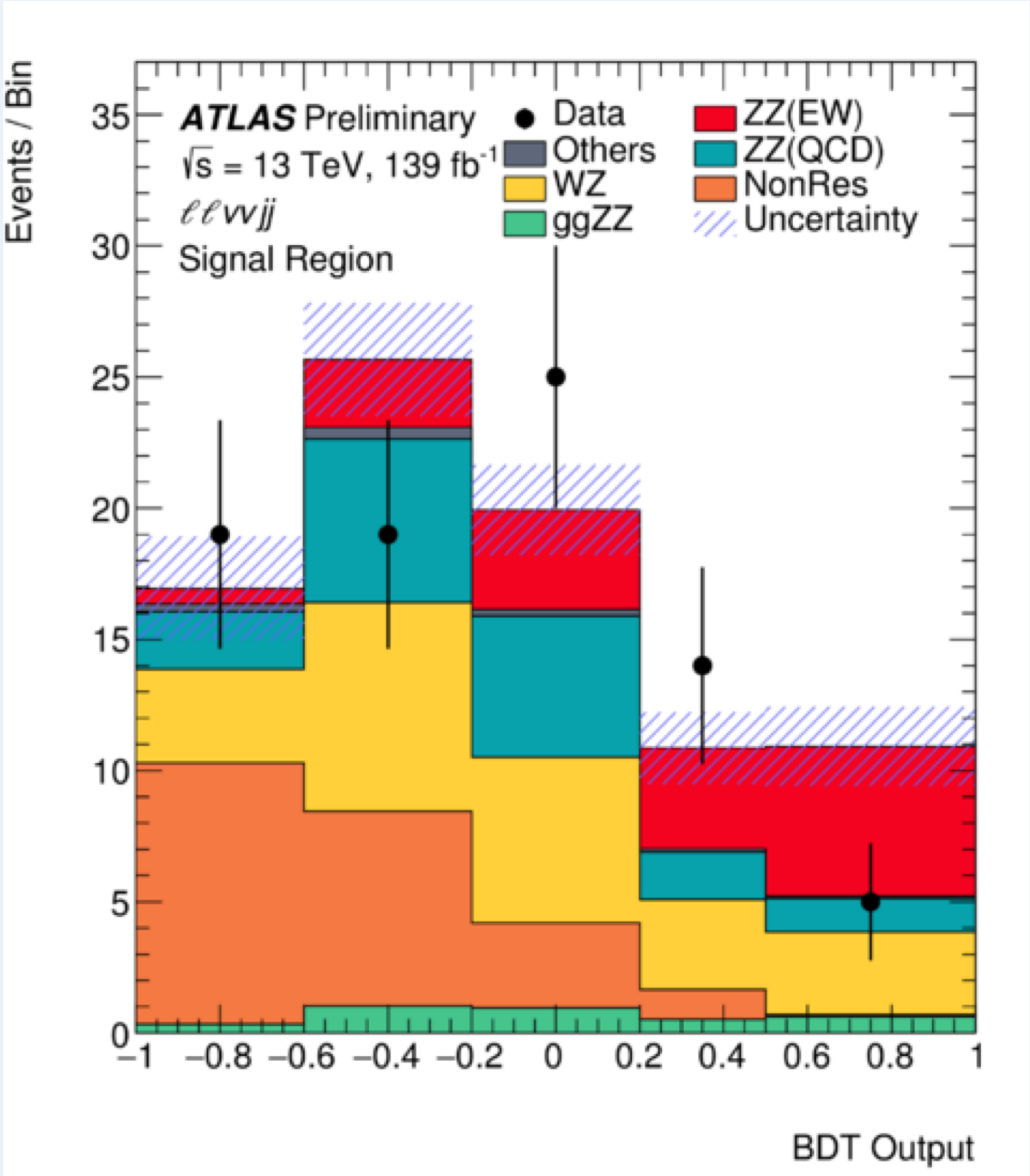
- Signal extraction:

with a 1D template fit using BDT score in both channels simultaneously with QCD CR

5.5 σ observation (4.3 expected)

- Fiducial cross section measurement (fb^{-1}):

$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$



ATLAS analysis strategy and results

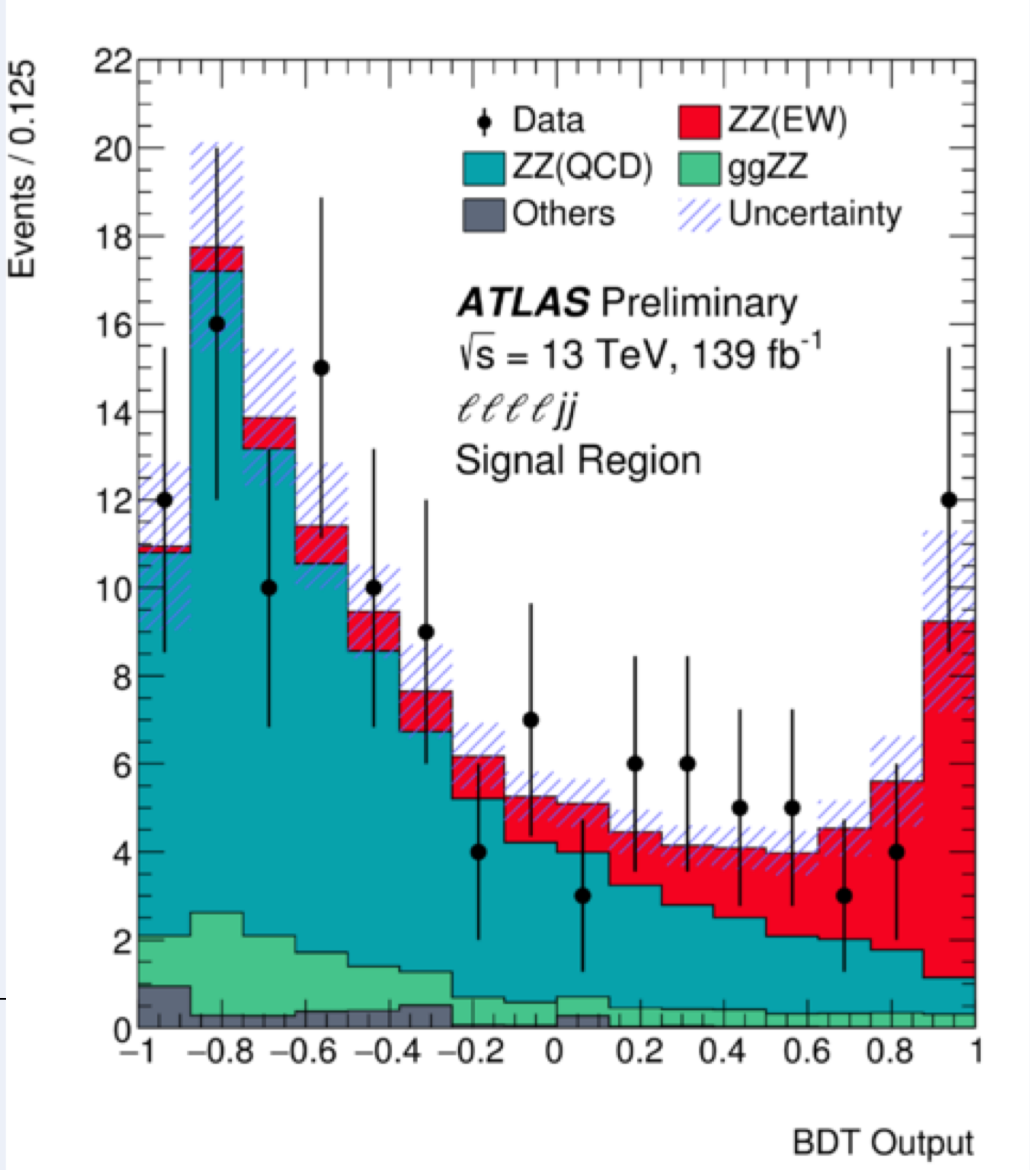
- Signal extraction:

with a 1D template fit using BDT score in both channels simultaneously with QCD CR, b-CR and ZZ-CR

5.5 σ observation (4.3 expected)

- Fiducial cross section measurement:

$$\begin{array}{l|l} \ell\ell\ell\ell jj & 1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi}) \\ \hline \ell\ell\nu\nu jj & 1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi}) \end{array}$$



Main sources of systematic uncertainty

ATLAS WZjj analysis

Source	Uncertainty [%]
Jets	6.7
Pileup	2.2
Electrons	1.6
Muons	0.7
b-tagging	0.3
MC statistics	2.1
Misid. lepton background	1.0
Other backgrounds	0.1
Theory ($WZjj$-EW)	5.0
Theory ($WZjj$-QCD)	2.3
$WZjj$-EW and $WZjj$-QCD interference	1.9
Luminosity	2.1

Main uncertainty: jet reconstruction and calibration

Theory uncertainties:

Low uncertainties from QCD scale and PDF
(flat wrt main kinematic variables)

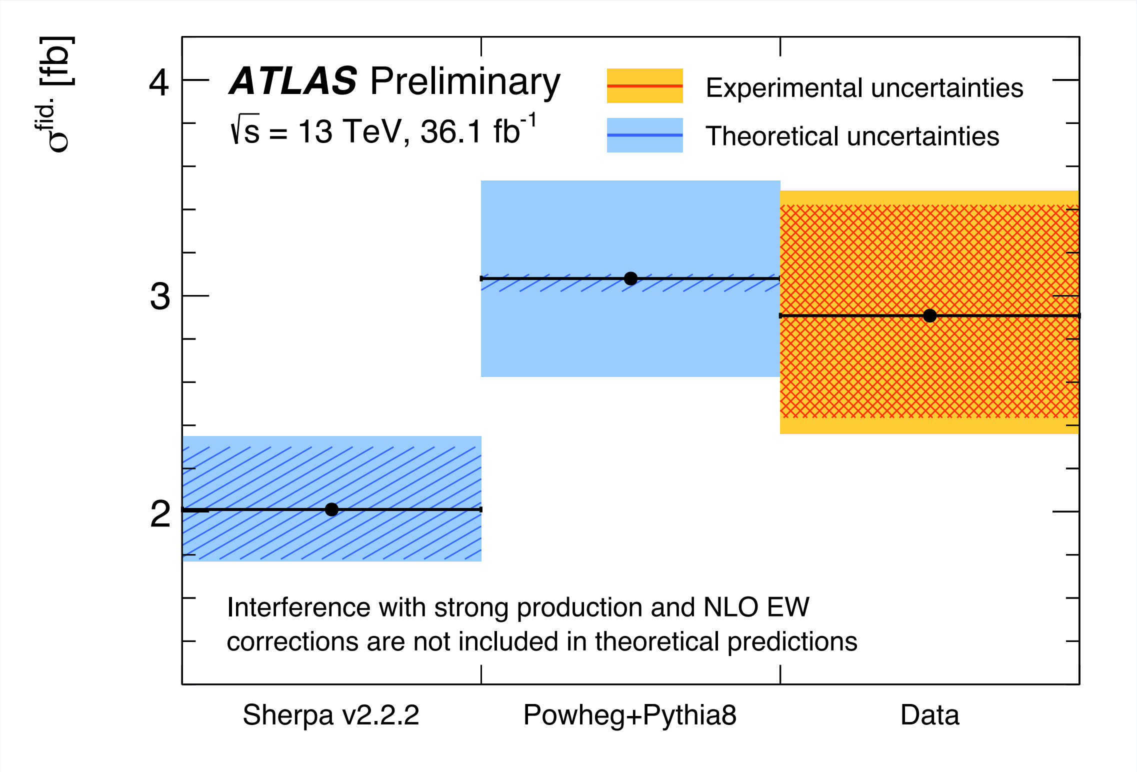
VERY important modelling uncertainties!!
(comparison on different generators)

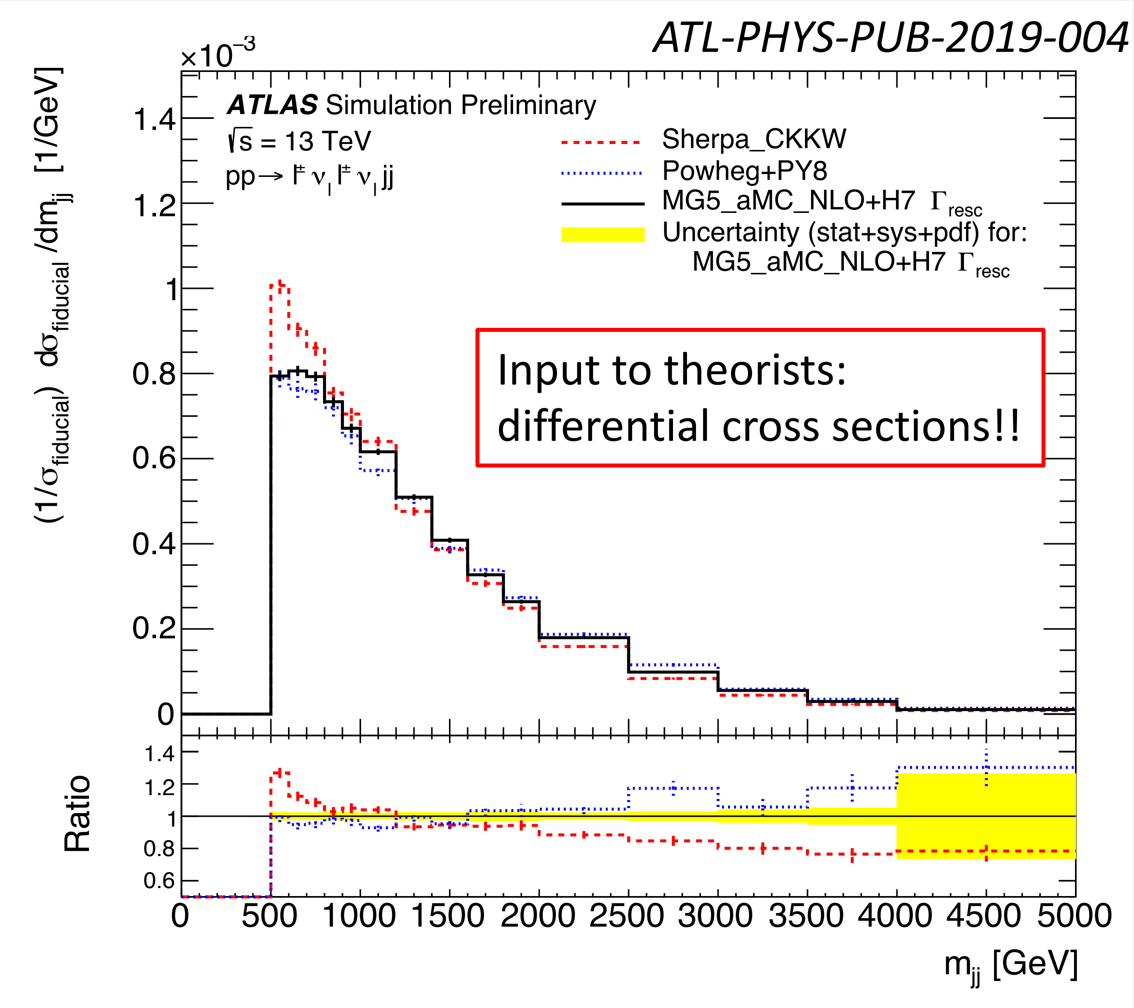
Interferences: *shape uncertainty*
Can we measure it directly with data?

Theoretical uncertainties

Important dependence on generator → high theoretical uncertainties on the measurement

from ATLAS W±W±jj analysis

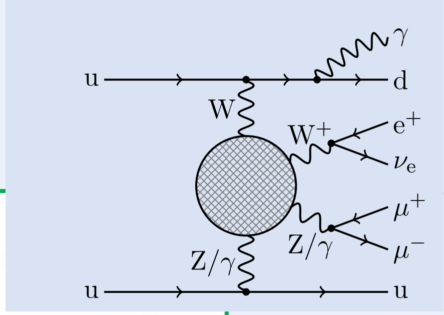




ATL-PHYS-PUB-2019-004

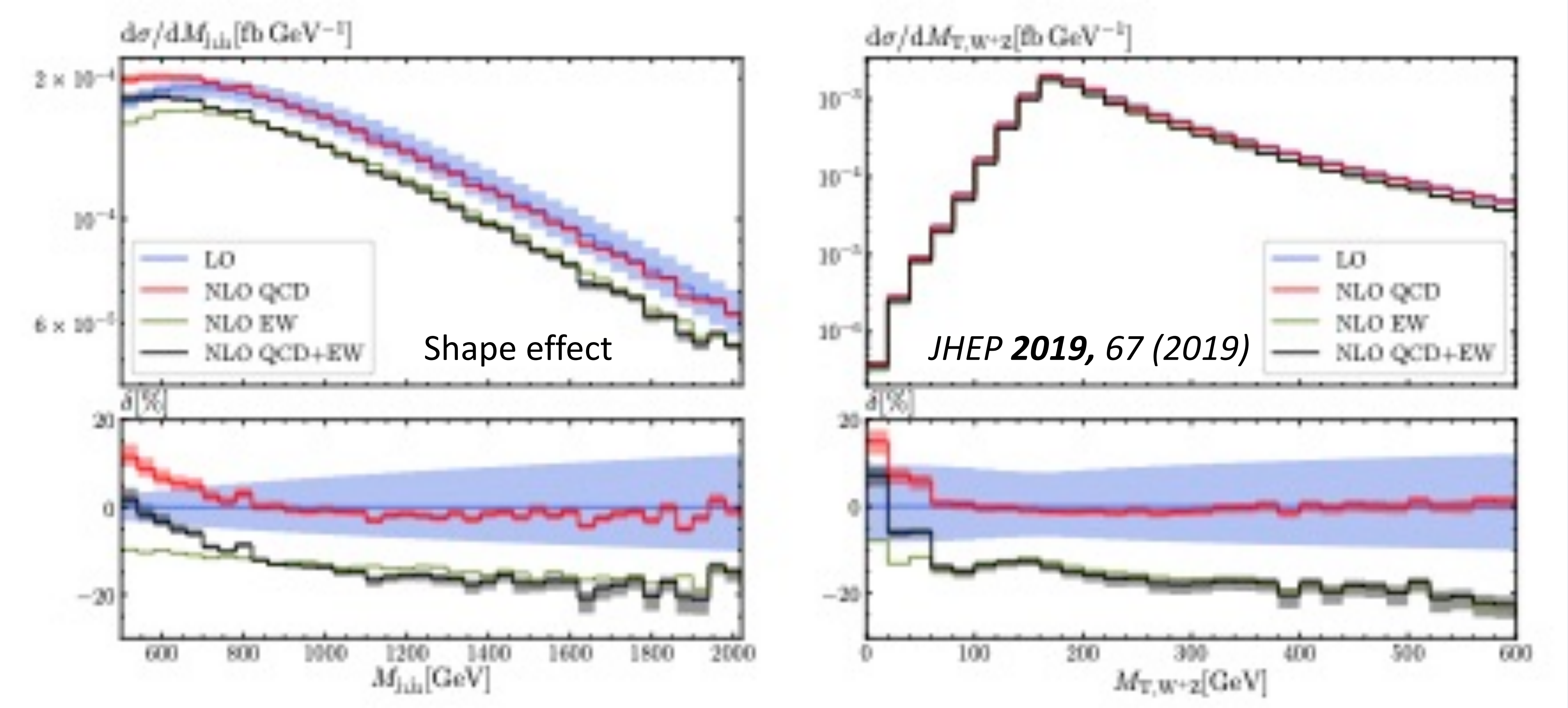
Input to theorists:
differential cross sections!!

Theoretical uncertainties



$$\begin{tikzcd}
 & \mathcal{O}(\alpha^6) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & & \mathcal{O}(\alpha_s\alpha^5) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & & \mathcal{O}(\alpha_s^2\alpha^4) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & \\
\boxed{\mathcal{O}(\alpha^7)} & & \boxed{\mathcal{O}(\alpha_s\alpha^6)} & & \mathcal{O}(\alpha_s^2\alpha^5) & & \mathcal{O}(\alpha_s^3\alpha^4)
\end{tikzcd}$$

- Important QCD and EW corrections
- Negative EW corrections (~ 15-20%)

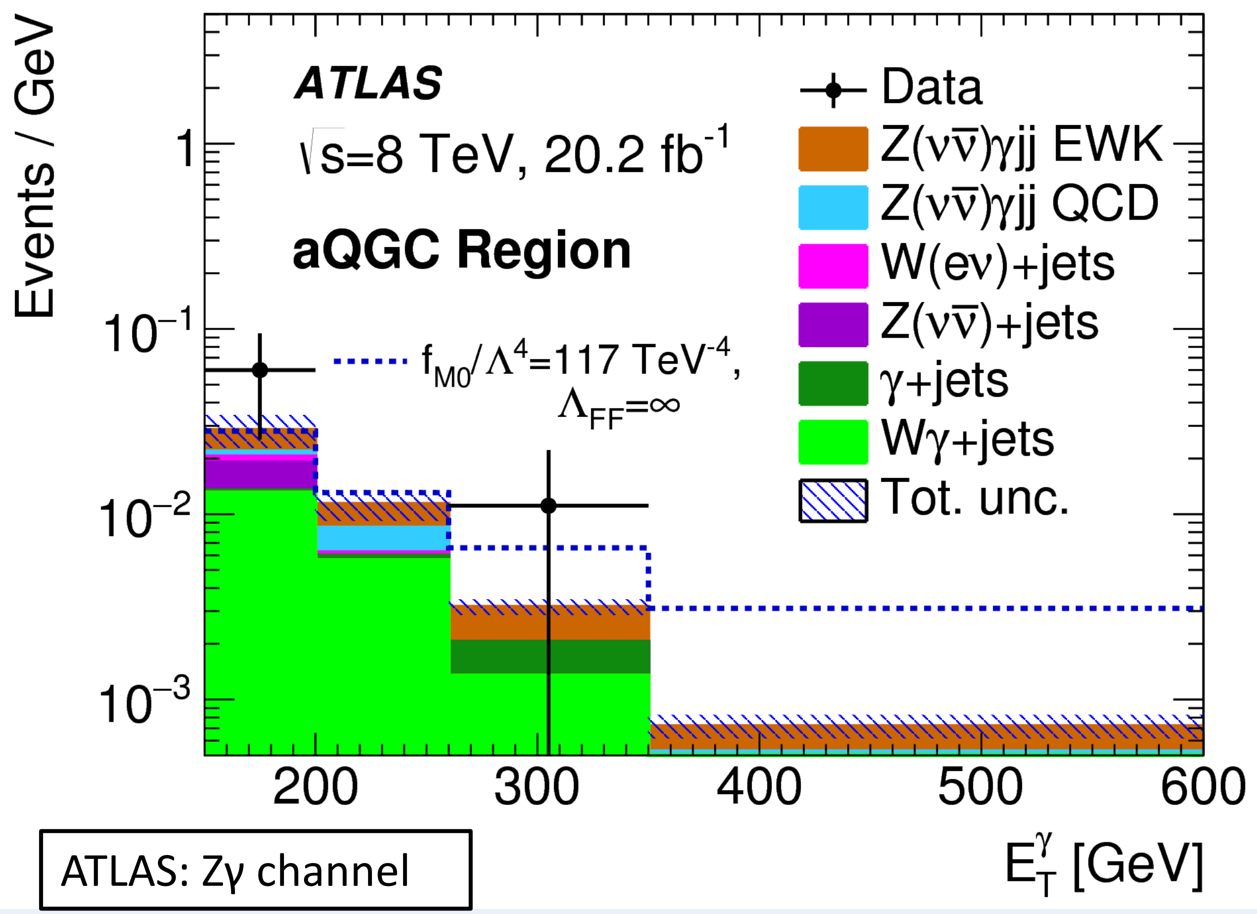


Shape effect

*JHEP **2019,** 67 (2019)*

Towards aQGC constraining

- Explore kinematic variables sensitive to aQGC (depending on the channel)
- aGQC would appear as **excess to the high energy tails**
- Usually constraint one aQGC parameter at the time



ATLAS: Zγ channel

Towards aQGC constraining

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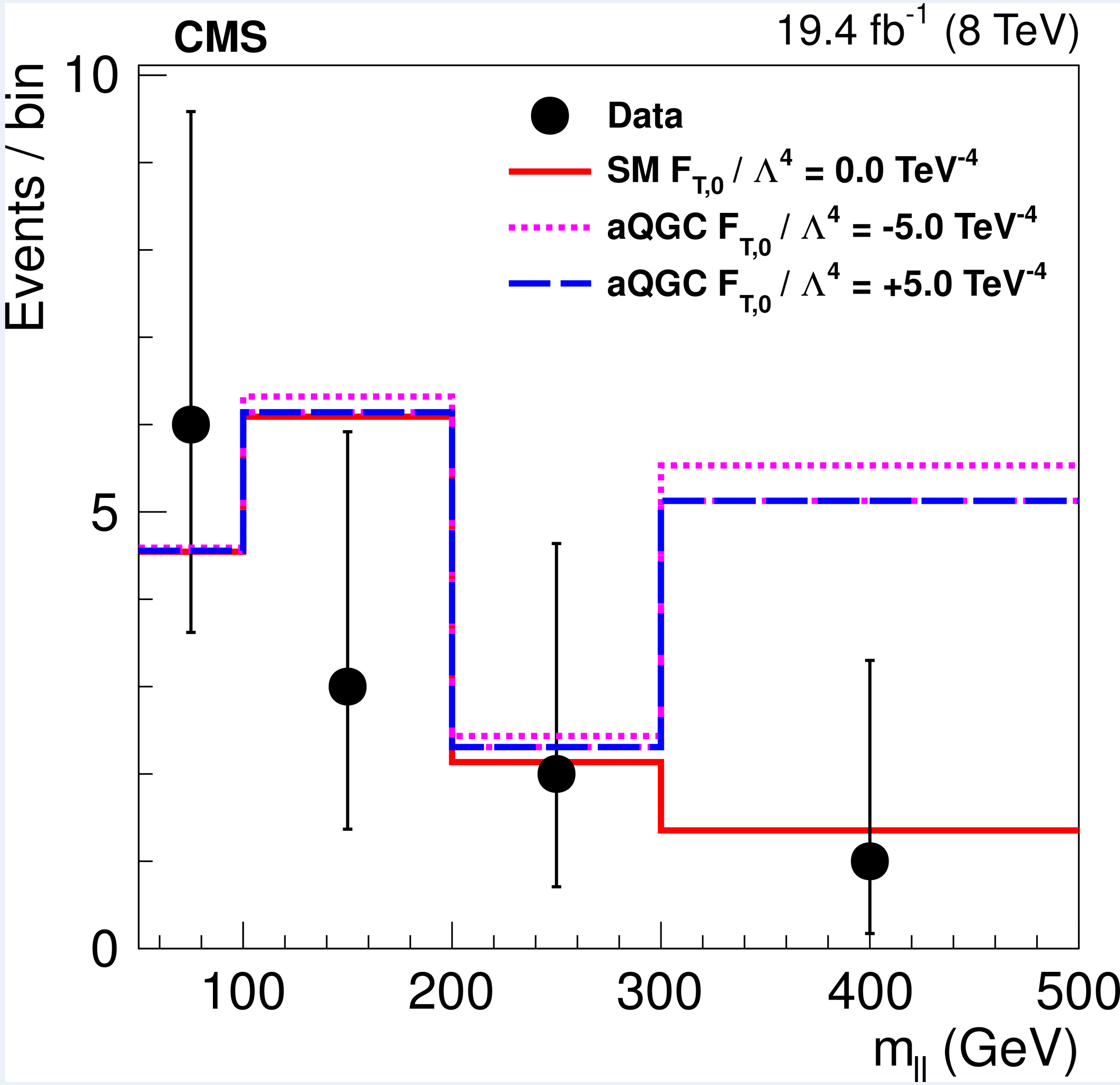
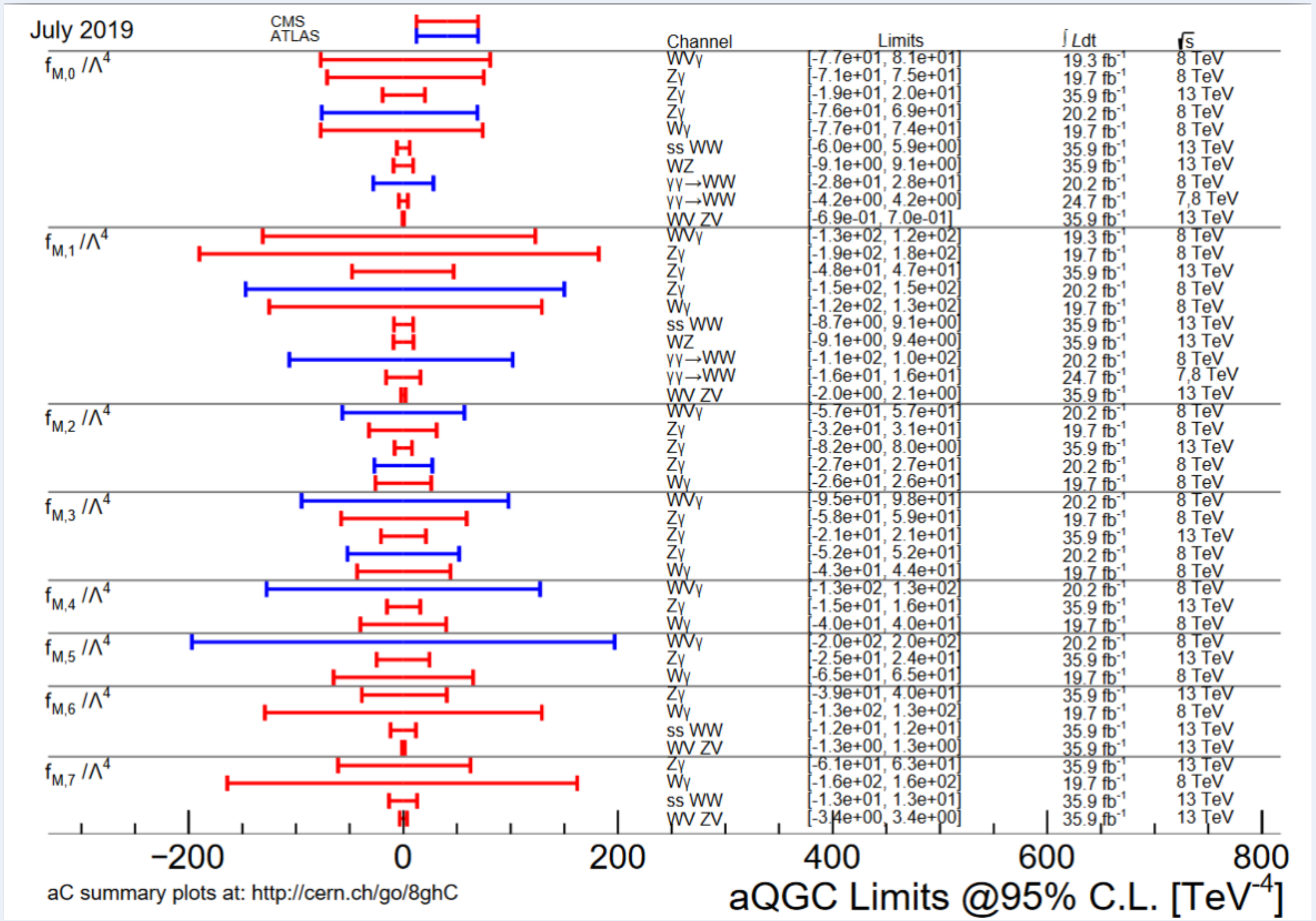


CMS: $W^{\pm}W^{\pm}$ channel

Limits on aQGC

- All explored aQGC parameters compatible with the Standard Model
- Both experiments have set constraints
- No comparison possible right now



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{M,0}/\Lambda^4$	WVγ	[-7.7e+01, 8.1e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-7.1e+01, 7.5e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.9e+01, 2.0e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-7.6e+01, 6.9e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-7.7e+01, 7.4e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-6.0e+00, 5.9e+00]	35.9 fb^{-1}	13 TeV
	WZ	[-9.1e+00, 9.1e+00]	35.9 fb^{-1}	13 TeV
	γγ→WW	[-2.8e+01, 2.8e+01]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-4.2e+00, 4.2e+00]	24.7 fb^{-1}	7,8 TeV
	WV ZV	[-6.9e-01, 7.0e-01]	35.9 fb^{-1}	13 TeV
$f_{M,1}/\Lambda^4$	WVγ	[-1.3e+02, 1.2e+02]	19.3 fb^{-1}	8 TeV
	Zγ	[-1.9e+02, 1.8e+02]	19.7 fb^{-1}	8 TeV
	Zγ	[-4.8e+01, 4.7e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-1.5e+02, 1.5e+02]	20.2 fb^{-1}	8 TeV
	Wγ	[-1.2e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-8.7e+00, 9.1e+00]	35.9 fb^{-1}	13 TeV
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	γγ→WW	[-1.1e+02, 1.0e+02]	20.2 fb^{-1}	8 TeV
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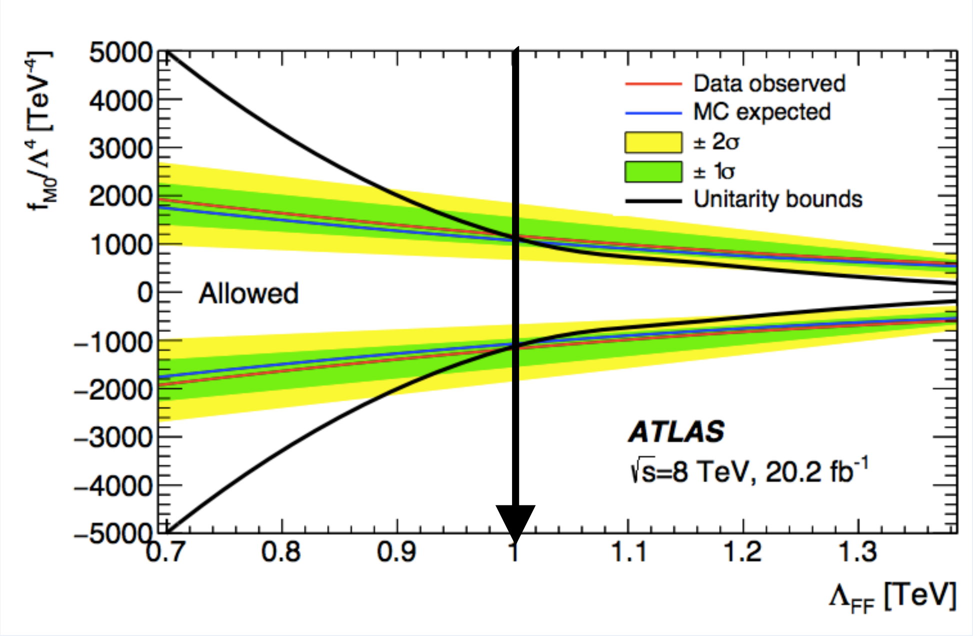
	WV ZV	[-2.0e+00, 2.1e+00]	35.9 fb^{-1}	13 TeV
$f_{M,2}/\Lambda^4$	WVγ	[-5.7e+01, 5.7e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-3.2e+01, 3.1e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-8.2e+00, 8.0e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-2.7e+01, 2.7e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-2.6e+01, 2.6e+01]	19.7 fb^{-1}	8 TeV
$f_{M,3}/\Lambda^4$	WVγ	[-9.5e+01, 9.8e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-5.8e+01, 5.9e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-2.1e+01, 2.1e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-5.2e+01, 5.2e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-4.3e+01, 4.4e+01]	19.7 fb^{-1}	8 TeV
$f_{M,4}/\Lambda^4$	WVγ	[-1.3e+02, 1.3e+02]	20.2 fb^{-1}	8 TeV
	Zγ	[-1.5e+01, 1.6e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-4.0e+01, 4.0e+01]	19.7 fb^{-1}	8 TeV
$f_{M,5}/\Lambda^4$	WVγ	[-2.0e+02, 2.0e+02]	20.2 fb^{-1}	8 TeV
	Zγ	[-2.5e+01, 2.4e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-6.5e+01, 6.5e+01]	19.7 fb^{-1}	8 TeV
$f_{M,6}/\Lambda^4$	Zγ	[-3.9e+01, 4.0e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.3e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-1.2e+01, 1.2e+01]	35.9 fb^{-1}	13 TeV
	WV ZV	[-1.3e+00, 1.3e+00]	35.9 fb^{-1}	13 TeV
$f_{M,7}/\Lambda^4$	Zγ	[-6.1e+01, 6.3e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.6e+02, 1.6e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-1.3e+01, 1.3e+01]	35.9 fb^{-1}	13 TeV
	WV ZV	[-3.4e+00, 3.4e+00]	35.9 fb^{-1}	13 TeV

aC summary plots at: http://cern.ch/go/8ghC

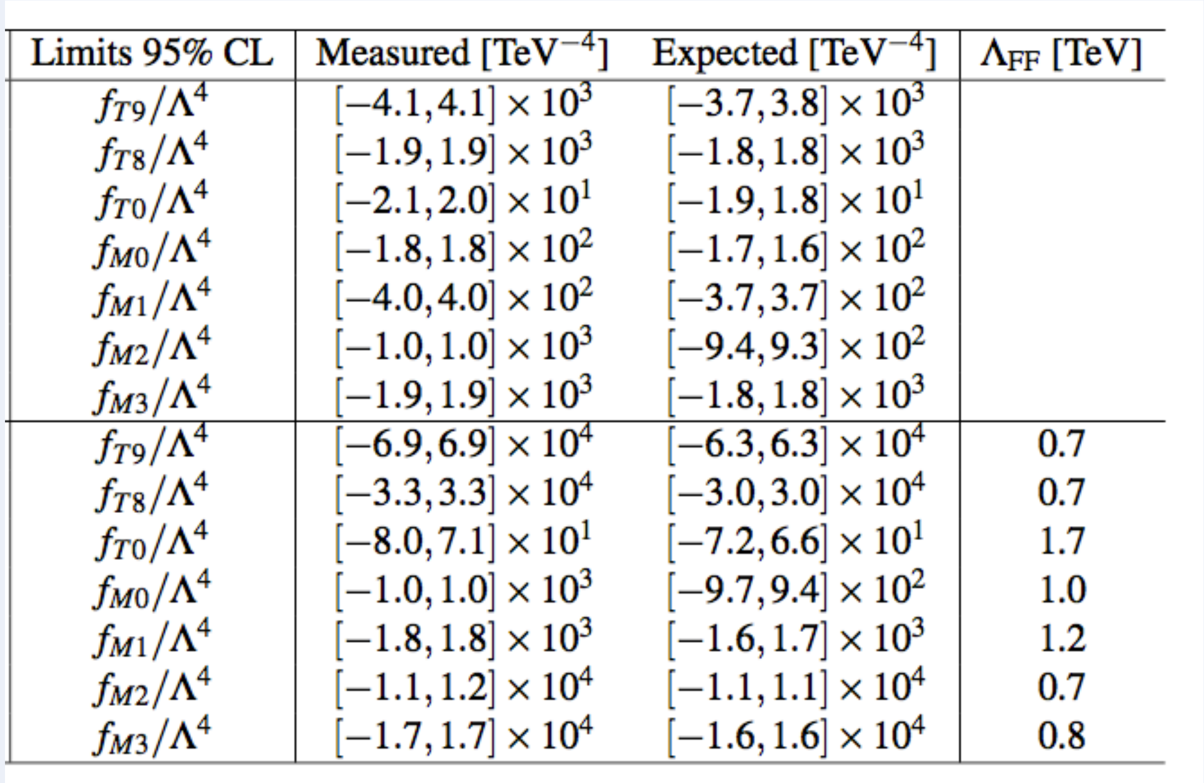
Limits on aQGC

- Unitarity problem: violated by the aQGC introduction



- Different treatment by ATLAS and CMS
- Towards a common decision

Zγ : CMS like

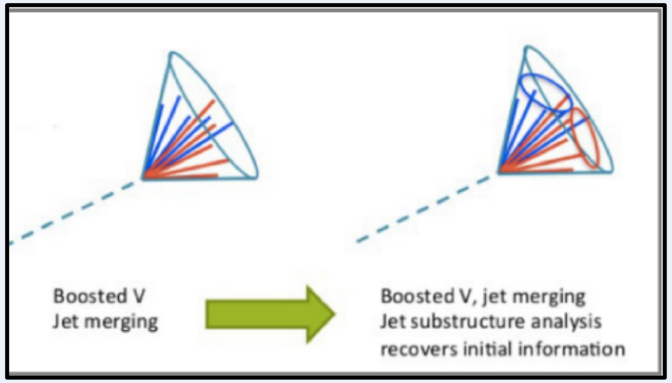


Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]	Λ_{FF} [TeV]
f_{T9}/Λ^4	$[-4.1, 4.1] \times 10^3$	$[-3.7, 3.8] \times 10^3$	
f_{T8}/Λ^4	$[-1.9, 1.9] \times 10^3$	$[-1.8, 1.8] \times 10^3$	
f_{T0}/Λ^4	$[-2.1, 2.0] \times 10^1$	$[-1.9, 1.8] \times 10^1$	
f_{M0}/Λ^4	$[-1.8, 1.8] \times 10^2$	$[-1.7, 1.6] \times 10^2$	
f_{M1}/Λ^4	$[-4.0, 4.0] \times 10^2$	$[-3.7, 3.7] \times 10^2$	
f_{M2}/Λ^4	$[-1.0, 1.0] \times 10^3$	$[-9.4, 9.3] \times 10^2$	
f_{M3}/Λ^4	$[-1.9, 1.9] \times 10^3$	$[-1.8, 1.8] \times 10^3$	
f_{T9}/Λ^4	$[-6.9, 6.9] \times 10^4$	$[-6.3, 6.3] \times 10^4$	0.7
f_{T8}/Λ^4	$[-3.3, 3.3] \times 10^4$	$[-3.0, 3.0] \times 10^4$	0.7
f_{T0}/Λ^4	$[-8.0, 7.1] \times 10^1$	$[-7.2, 6.6] \times 10^1$	1.7
f_{M0}/Λ^4	$[-1.0, 1.0] \times 10^3$	$[-9.7, 9.4] \times 10^2$	1.0
f_{M1}/Λ^4	$[-1.8, 1.8] \times 10^3$	$[-1.6, 1.7] \times 10^3$	1.2
f_{M2}/Λ^4	$[-1.1, 1.2] \times 10^4$	$[-1.1, 1.1] \times 10^4$	0.7
f_{M3}/Λ^4	$[-1.7, 1.7] \times 10^4$	$[-1.6, 1.6] \times 10^4$	0.8

Zγ : ATLAS like

Semi leptonic channels

Combination of WW, ZZ and WZ channels



Selection:

- One leptonically decayed boson
- One hadronically decayed boson
- At least two high P_T forward jets

CMS:
Phys. Lett. B 798, 134985 (2019)

ATLAS:
Phys. Rev. D 100, 032007 (2019)
Phys. Rev. D 95, 032001 (2017)

Very challenging analysis but with high theoretical interest

- Jet substructure techniques allow to explore high-Pt regions
- High sensitivity to aQGCs

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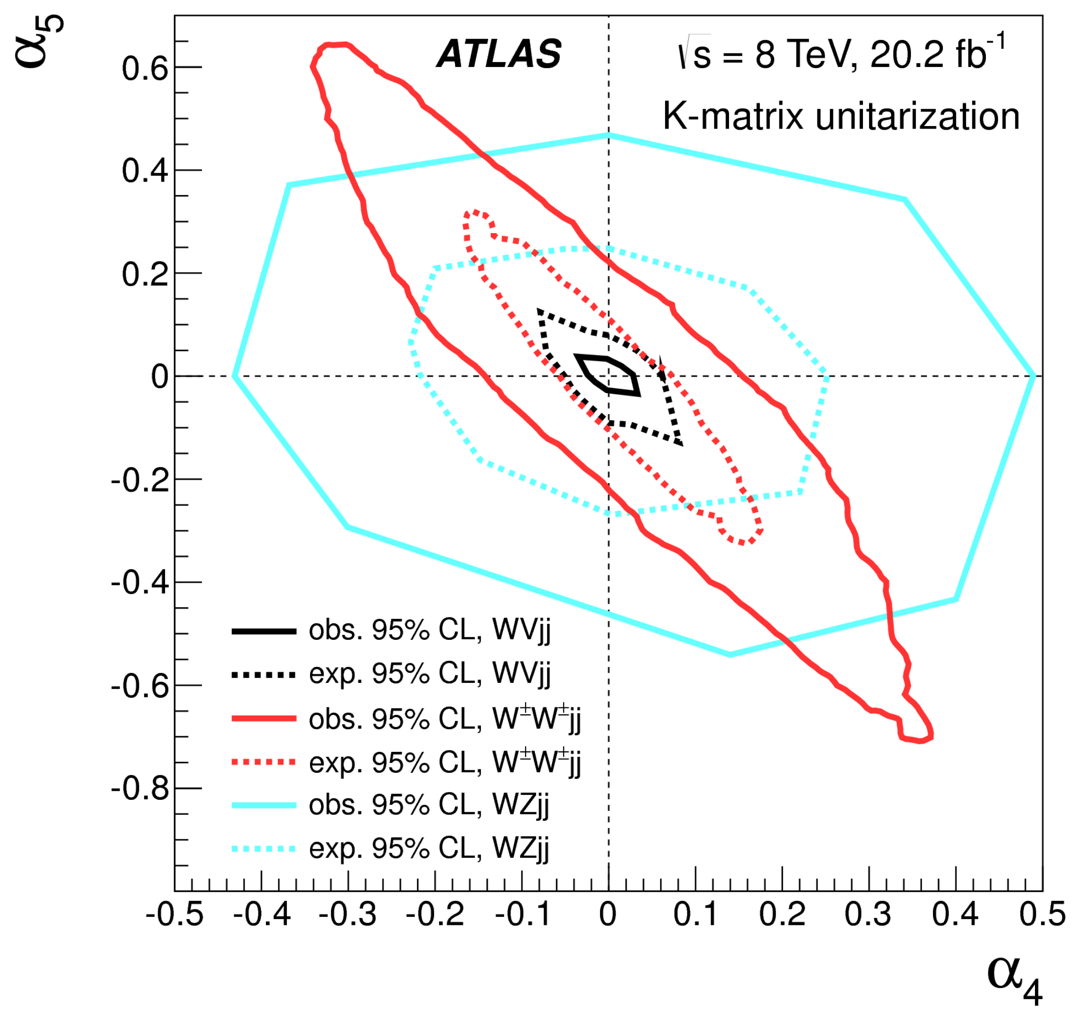
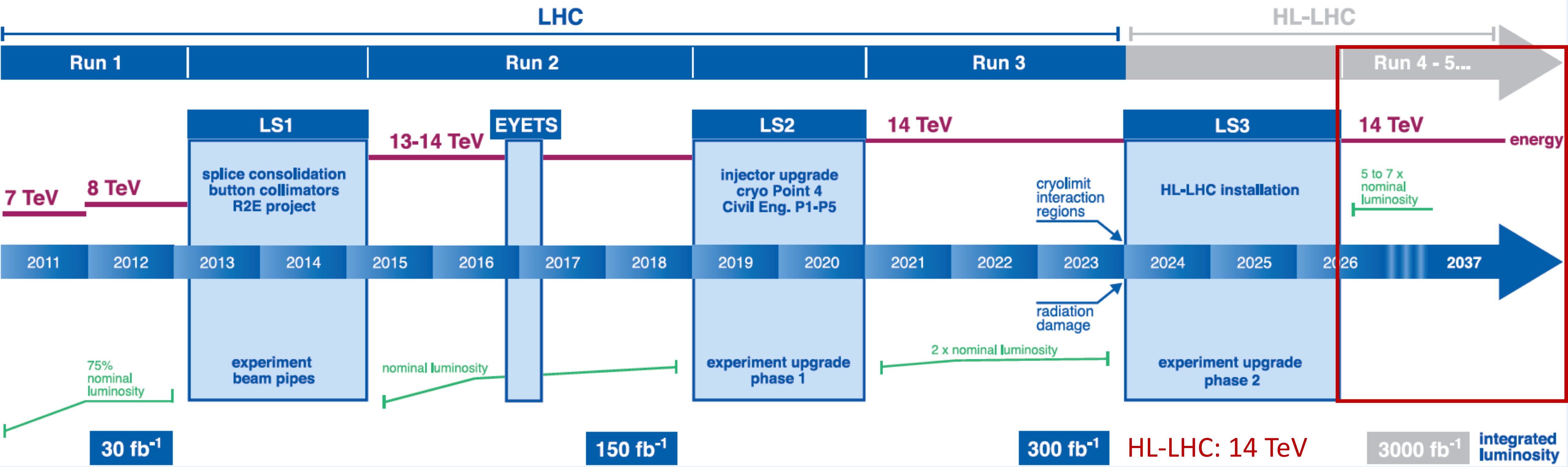


Vector Boson Scattering: long term future



HL-LHC: 14 TeV

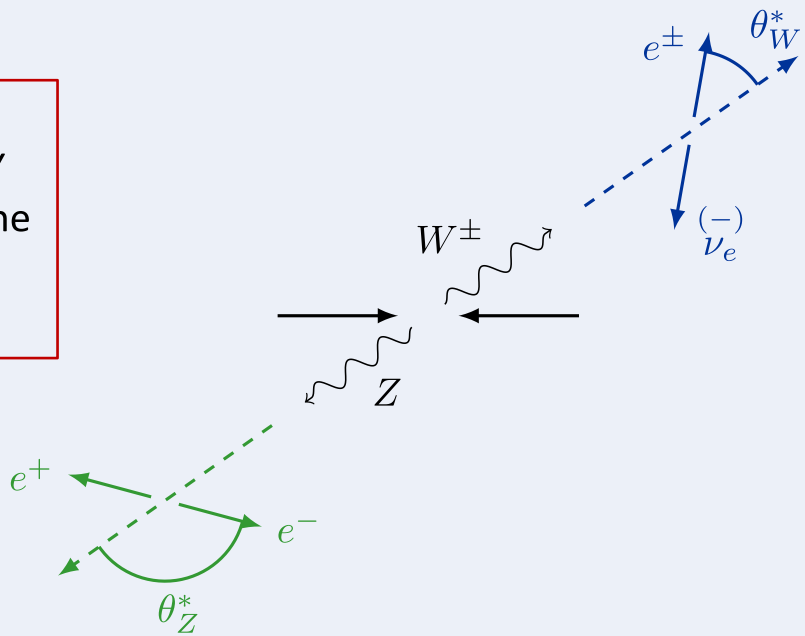
- Up to 3000 fb^{-1} could allow us to reach very detailed VBS features, such as polarized states scattering (such as $V_L V_L$)

- This will also need an important improvement from the performance and analysis techniques side, using for example advanced machine learning techniques

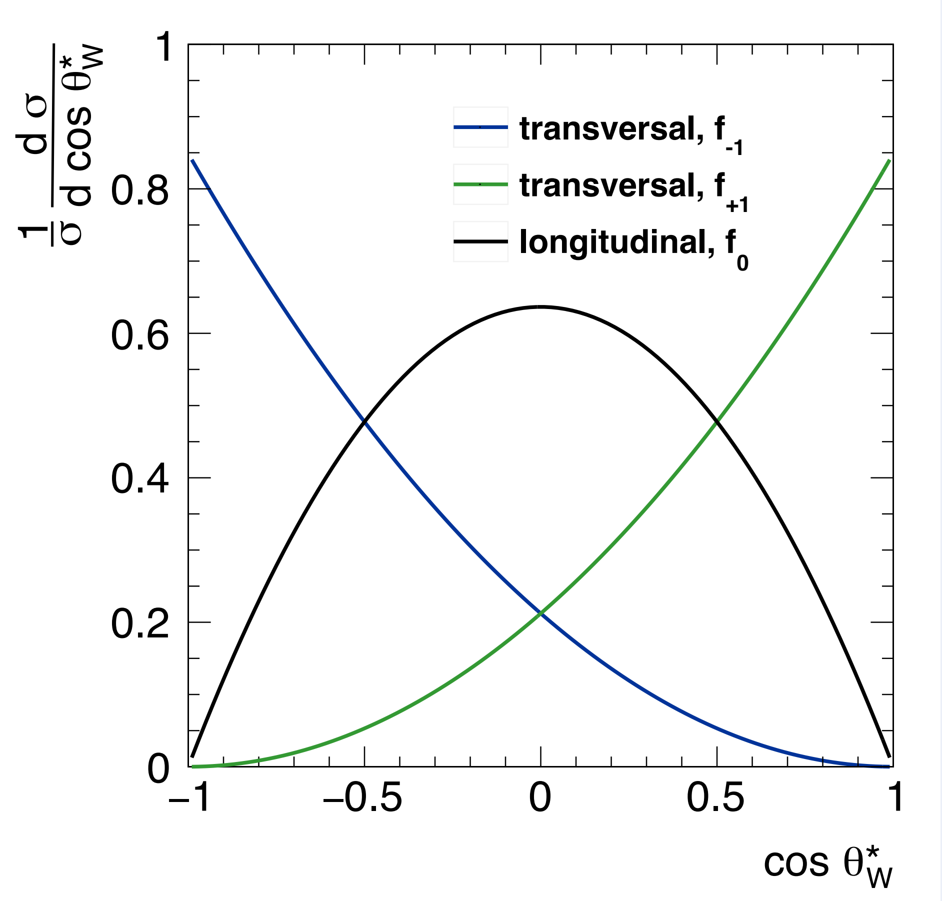
Longitudinal polarization in VBS

- $V_L V_L \rightarrow V_L V_L$ deeply linked to the EWSB
- Without it, unitarity would be violated
- Important test to the SM

Decay angle of the charged lepton in the *V* rest frame relative to the *V* direction in the *VV* centre-of-mass frame



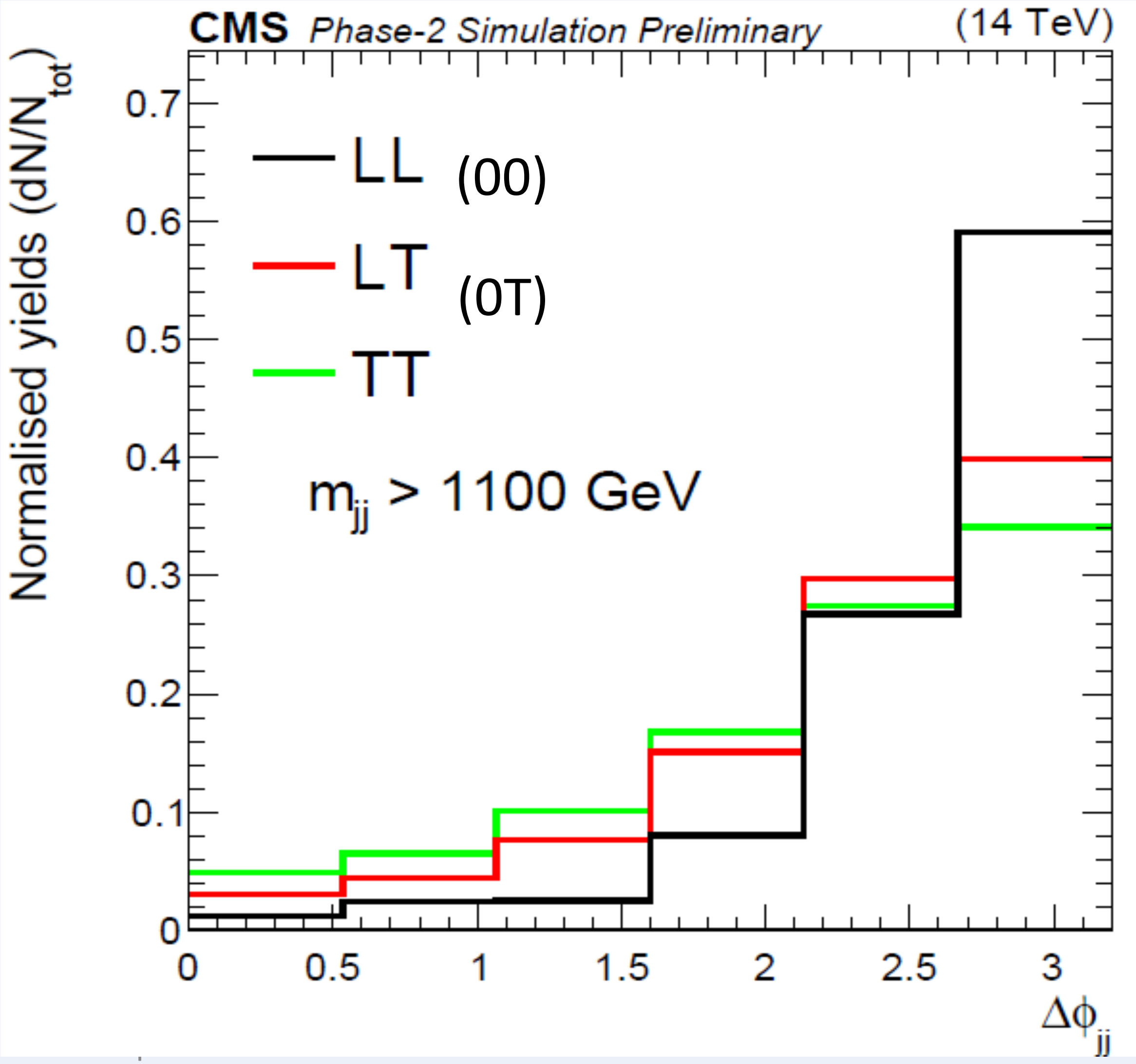
C. Bittrich, CERN-THESIS-2015-039



Decay angle for the three polarization states

Longitudinal polarization in VBS

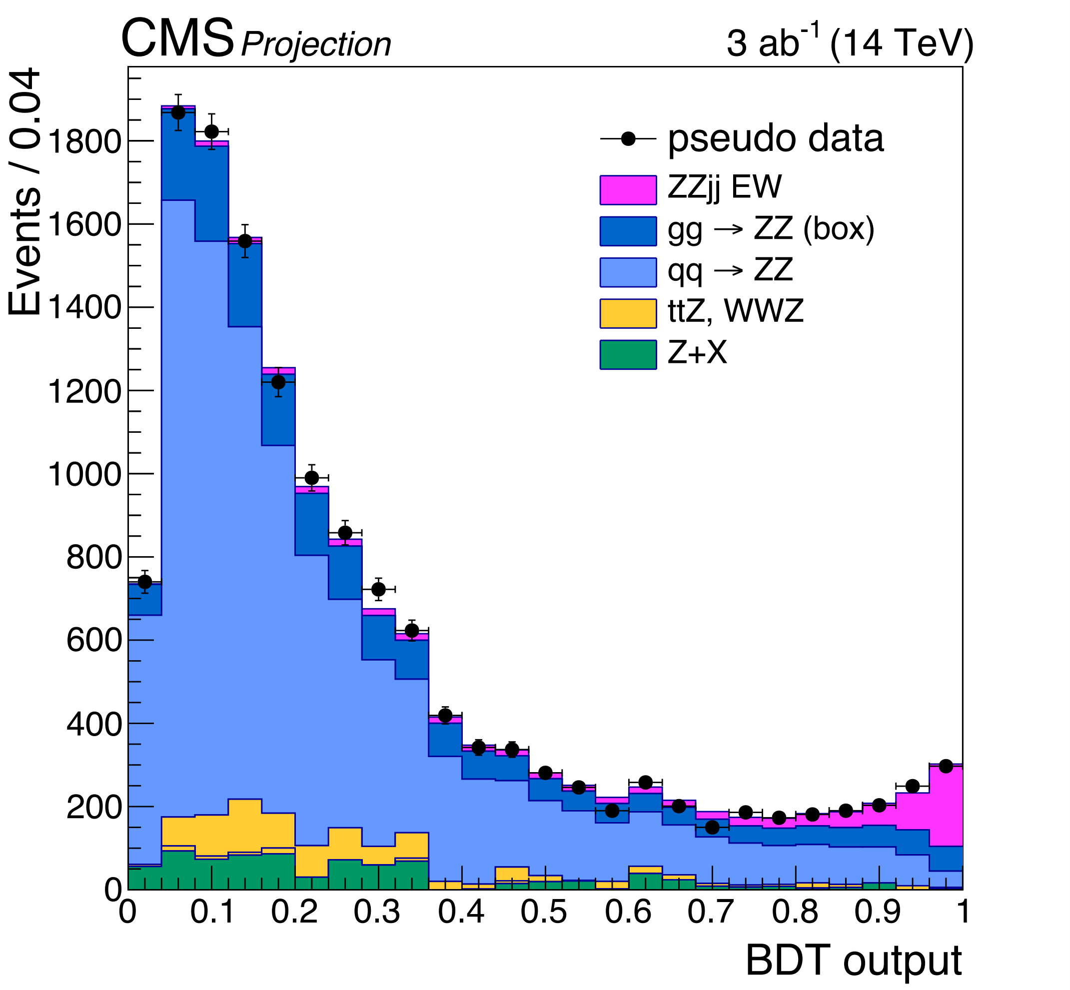
- Very chalenging experimentaly
- Very low cross section
- $W_L Z_L$ only 5% of the total WZ
- Must exploit all kinematic differences between the different polariuzation states
- Machine Learning analyses?



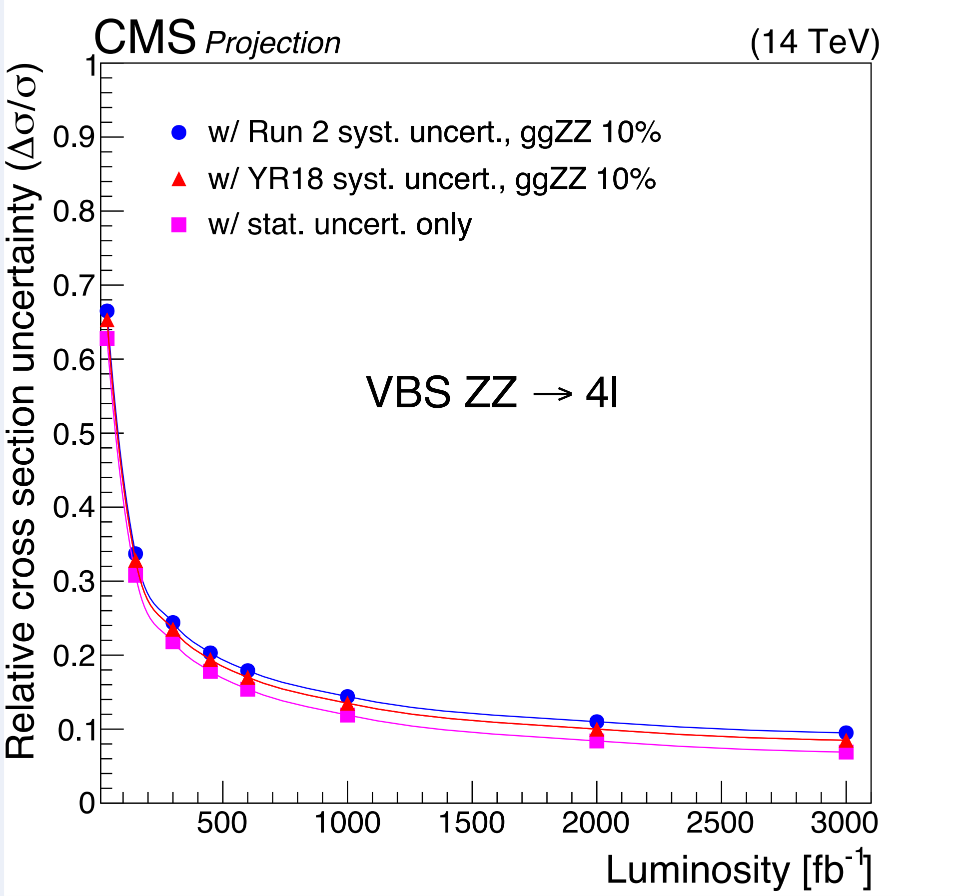
HL-LHC projection for the ZZ channel

- **700 expected events** in the fully leptonic final states
- Important improvement on the cross section uncertainty
- Study of the V_LV_L channel
- Results for 6000 fb^{-1}

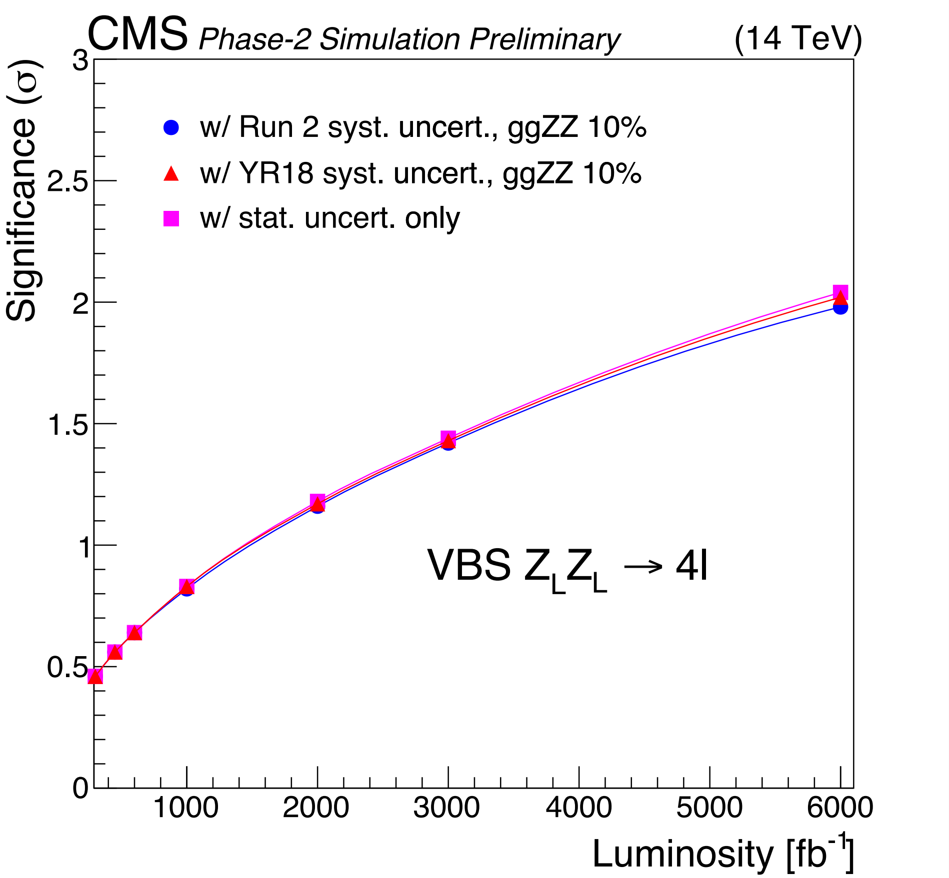
(approximately ATLAS-CMS combination)



HL-LHC projection for the ZZ channel



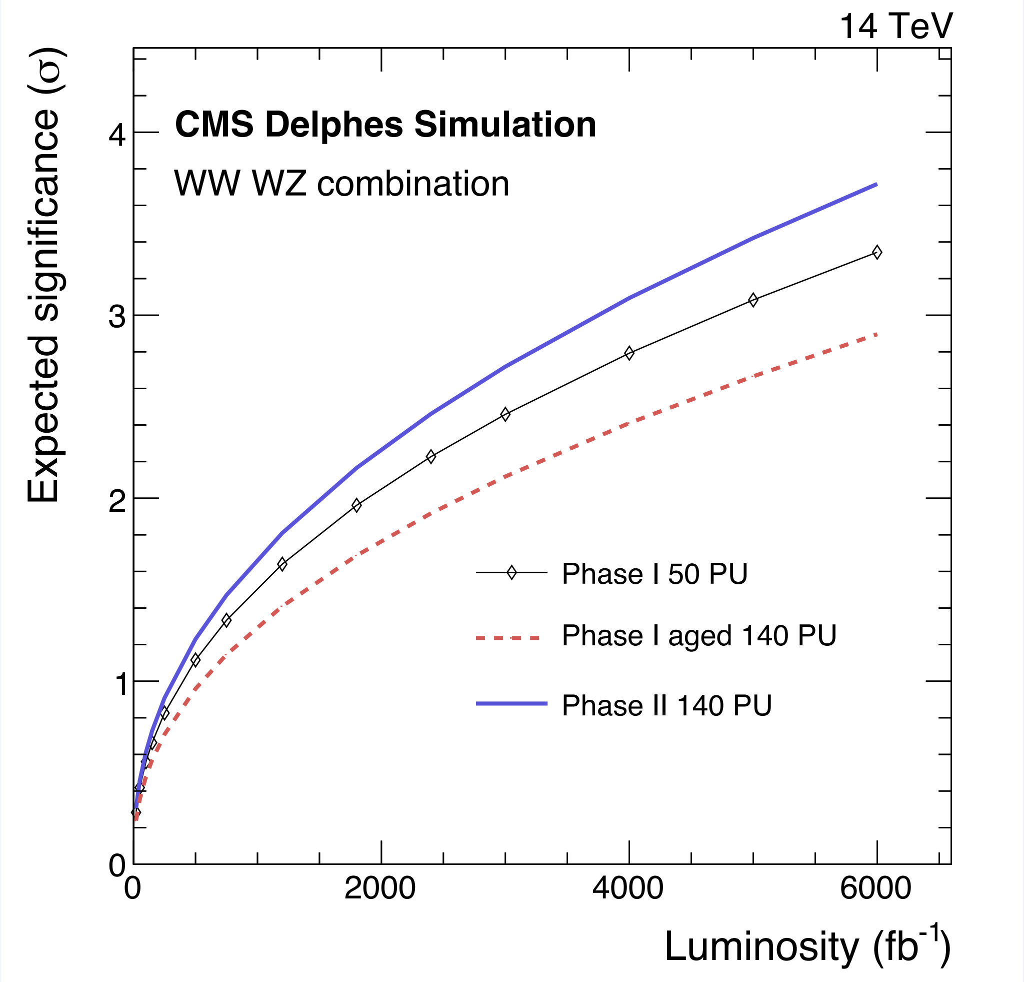
Improvement on the cross section uncertainty



Increasing sensitivity to the Z_LZ_L channel

HL-LHC projection for the WZ and $W^{\pm}W^{\pm}$ channels

- Almost 3000 events expected for WZ and more than 5000 for WW
- Similar improvement on the cross section measurement
- A first combination attempt suggests a possible $V_LV_L \rightarrow V_LV_L$ evidence before the end of HL-LHC



Conclusions

- Vector Boson scattering became accessible with Run 2 LHC data
- Electroweak diboson production was observed in the $W^{\pm}W^{\pm}jj$, WZjj and ZZjj final states
- More channels to come (Zγjj, semileptonic channels)
  - will alllow to study different quartic boson couplings
  - could lead to combination studies
- Full Run 2-3 and, in the longer term, HL-LHC statistics will allow further interpretation studies
  - Anomalous quartic gauge boson couplings
  - polarized VBS: probably access the pure $V_LV_L \rightarrow V_LV_L$ scattering
- Need to progress on:
  - Experimental analysis techniques (probably using machine learning)
  - Performance studies (high pile-up conditions, quark-gluon discrimination…)
  - Theoretical calculations (and way to include them into the analysis)